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CHANGES IN HELICOPTER RELIABILITY/ MAINTAINABILITY CHARACTERISTICS OVER TIME. VOLUME 1. BASIC REPORT

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Institute for Defense Analyses

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INSTITUTE FOR DEFENSE ANALYSES
PROGRAM ANALYSIS DIVISION

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This report examines the growth (or lack of it) in reliability and maintainability (R&M) characteristics of past helicopter programs and [illegible] the data so that they can be used as bases for predicting the R&M characteristics of future helicopter programs. Six types of R&M data are presented: (1) failure rates, (2) component-removal rates, (3) [illegible] rates, (4) maintenance-action rates, (5) operational

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availability, and (6) maintenance man-hours. Many of the data on past helicopter programs are included in the report, so that they will be available for use by analysts.

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SUMMARY

The basic objectives of this study are to examine the growth (or lack of it) in reliability and maintainability (R&M) characteristics of past helicopter programs and to organize the data so that they can be used as bases for predicting the R&M characteristics of future helicopter programs.

We were able to obtain time-series data for six R&M measures: (1) failure rates, (2) component-removal rates, (3) mishap rates, (4) maintenance-action rates, (5) operational availability, and (6) maintenance man-hours. Though all these measures are to varying degrees interrelated, it is believed that they are sufficiently different to warrant discrete treatments. Each measure is discussed separately below. The need for standardization of both R&M definitions and methods of data presentation can often be seen. The data presented for each measure in the basic report are discussed briefly, and the location in the report is identified for easy reference. A general conclusion for each R&M measure is presented.

Duane [26] found that for some equipments cumulative failure rate versus cumulative operating hours resulted in a straight line when the data points were plotted on log-log paper. He expressed these "Duane curves" by the equation

$$CFR = \lambda t^{-\alpha} ,$$

where

CFR = cumulative failure rate;

λ = initial failure rate (intersection at t = 1 hour);

t = cumulative operating hours; and

α = exponent.

$-\alpha$ denotes the slope of the cumulative failure-rate line: when α is positive, there is a decreasing failure rate; when it is negative, there is an increasing failure rate. Because of the convenience of the Duane formulation, we have calculated α's for some of the reliability measures discussed below.

The Duane paper presented data for five equipments whose α's fell in the range of 0.4 to 0.5. Because of the scarcity of reliability-growth data, the Duane data (α's of about 0.5) have been used in predicting reliability growth for many other equipment programs, including helicopters. However, the helicopter data presented herein indicate that α's for various measures of helicopter reliability tend to be much lower; and even some cases of negative α's were found.

A. FAILURE RATES

Failure rate (sometimes referred to as "malfunction rate"), the most common measure of reliability, is expressed in several forms. Two categories of failures are often used in specifying helicopter reliability: (1) all failures,[1] and (2) failures that are sufficiently serious to cause cancellation or termination of a mission ("mission abort").

Failures are sometimes described as a rate (e.g., 25 failures per 100 flight-hours could be expressed as a failure rate of 0.25 per hour). They may also be described by "mean time between failures" (MTBF). In the example above, MTBF = 100 ÷ 25 = 4.0 hours. If the failure rate is constant, it can be used to determine the probability of completing a mission by use of the expression $e^{-\lambda t}$, where λ is the failure rate and t is the mission duration in hours. For a failure rate of 0.25 per hour (hypothesized above), the probability of completing a one-hour mission without a failure would be 0.779; and the probability of

[1]A failure is the inability of an item to perform within previously specified limits.

completing a 1.5-hour mission would be 0.687. The probability of completing a mission without any failure is usually called "total reliability," "system reliability," or "maintenance reliability"; and the probability of completing a mission without a mission-aborting failure is called "mission reliability" or "operational reliability." Mission-aborting failure rate (per flight-hour) is often referred to as abort rate, which is sometimes also expressed as "mean time between aborts" (MTBA), calculated in the same manner as MTBF but based on mission-aborting failures only, rather than on all failures. To standardize these many ways in which failure rates are reported, we recommend that MTBF be used as the primary form of failure reporting, and then be qualified as to whether it includes all failures ("system failures") or only mission-aborting type failures ("mission failures").

Under the various terms discussed above, the following data involving failure rates are presented in this study (see pp. vi-xii, below, for pages on which the figures and tables appear):

(1) The failure rates for individual CH-47A aircraft in Army operations worsen as the aircraft accumulate flight-hours (Figure 1).

(2) When the OH-58A was introduced into Army service, it underwent a 15-month R/M demonstration. The MTBF initially was relatively high (probably reflecting the fact that the aircraft were new), but during the first three months it dropped to a level that stayed fairly constant for the remainder of the program (Figure 4).

(3) The MTBA for the OH-58A worsened somewhat during the first two years of Army service (Figure 5).

(4) Both the maintenance and operational reliabilities of the UH-1D worsened over the first 13 months of Army operation (Figure 9).

(5) The MTBA for the CH-54A remained approximately constant over four years of Army service (Figure 11).

(6) The MTBF for all helicopters in Navy service decreased (worsened) over the period 1968-73 (Figures 15, 18, 21, 24, 27, 30, 33, and 36).

(7) Based on all failures for a 52-month flight-test program, α for the AH-56A was 0.16. For nine sub-

systems, the α's ranged from -0.14 to +0.33 (Figures 49-58). (The AH-56A development flying covered almost five years, and the program was cancelled without ever reaching service use. Compared with the other development programs for which data are available, it appears that the AH-56A reliability growth may have been somewhat slower than that of "successful" development programs.)

(8) During the first 16 months of ground testing, the T700 engine has shown a slight improvement: $\alpha = 0.03$, on the basis of all failures (Figure 62); or $\alpha = 0.09$, if failures for which "fixes" have been accepted are eliminated (Figure 63).

(9) Failure rates generally improved in successive models of of the T53 engine family (Figures 66 and 67).

(10) α for malfunctions per flight-hour for the CH-47 was 0.063 in Duane notation (or -0.063 in Boeing Vertol notation) for the period 1963-72. The system α's ranged from 0.315 to -0.160 for the period 1965-72 (Vol. 2, Part A, Table 2, p. BV-29).

(11) α for malfunctions per flight-hour for the CH-46 was 0.218 for the period 1962-72. However, all the improvement took place from 1962 to 1970; it worsened from 1970 to 1972. Data for systems are available only from 1968 to 1972, during which time they showed a slight reliability degradation; average α for 23 systems was -0.089 (Vol. 2, Part A, Table 7, p. BV-116).

(12) The failure rate of the OH-6A remained approximately constant for the first 1,000 flight-hours and then improved ($\alpha = 0.35$) from 1,000 to 27,000 flight-hours (Figure 81).

(13) Based on development and early production of the UH-1D, AH-1G, and OH-58A, the MTBF at 100 flight-hours was 20-30 percent of the MTBF for the mature production aircraft (Ch. V, Sec. C).

(14) MTBF/total reliability for the CH-54A/B program generally worsened over the period 1968-74 (Table 46).

(15) Abort rate/mission reliability for the CH-54A/B program generally improved over the period 1968-74 (Table 46).

(16) There was a marked decrease in abort rate for the CH-53, from about 0.25 at 100 flight-hours to about 0.07 when the aircraft was introduced into field service (after about 5,000 flight-hours).

From the start of the flight-test program to early field service, α was in the range 0.3-0.4. The abort rate in field service dropped to about 0.03 after 40,000 flight-hours, but then it rose to about 0.04 at 100,000-150,000 flight-hours (Figure 86).

General Conclusions. Items (7), (8), (12), (13), and (16) above provide data on the early-development flying (or, in the case of the T700 engine, ground-test) portions of the programs. All indicate failure-rate improvement during this portion of the program. From the start of the flight-test program to early field service, α's range from 0.16 for the AH-56A to about 0.35 for the OH-6A and CH-53A. Items (12), (13), and (16) cover both development and service experience; they indicate that MTBF at 100 hours is about 16-30 percent of the MTBF for the mature-production aircraft. The 16 percent is based on CH-53 aborting failures. It is probable that aborting failures (being more serious in nature) receive more corrective attention than failures in general. Hence, the lower part of the 16-30 percent range may be more representative of aborting failures, while the higher part of this range is more representative of all failures. During field service, failure rates in general appear to worsen over time--which is probably due to the aging of the fleet, the tendency to add equipment to the aircraft, the tendency to increase engine power, and the assignment of the better maintenance and operating service personnel to the newer programs.

B. COMPONENT REMOVAL RATES

Major components of helicopters (e.g., transmissions, rotor heads, and blades) are removed from the helicopter and sent to a depot or factory for overhaul. Often these components have a time between overhaul (TBO) established for them. With a TBO, the component must be removed and overhauled when it has accumulated the specified number of hours, even though it has not failed; such removals are scheduled removals. Some components

have no TBO and are removed "on condition" (i.e., when failure occurs). In addition, because of failures, components with TBOs may have to be removed prematurely. These removals because of failure are unscheduled removals. Hence, we have three basic classes of removal data: TBO, unscheduled removals, and all removals (scheduled and unscheduled). As in the case of failure data, removal data may be presented either as removal rate per flight-hour (or per 1,000 flight-hours) or as a mean time between removals (MTBR). MTBR is usually based on total-fleet flight-hours divided by total number of removals. However, data are sometimes collected for individual components (in which case, the actual number of flight-hours on the component since new or last overhaul is reported). This type of data is designated mean time to removal (MTTR). We recommend that removal data be reported as either MTBR or MTTR, since this format is directly comparable to the reporting of TBOs, which are always reported as time between overhauls--never as overhaul rates per flight-hour. Under the various labels discussed above, the following data involving removal rates are presented in this study:

(1) MTTRs for OH-58A components generally showed increases from 1969 to 1972. However, even though the components were not improving over this period, their reported MTTR would tend to increase as they accumulated time. Hence, the MTBR (not the MTTR) was probably approximately constant (Figure 6).

(2) MTTRs for AH-1G components generally showed decreases from 1969 to 1971. Because MTTRs tend to increase during early service operation, this decrease in MTTRs would indicate strongly that MTBRs were worsening over this period (Figure 10).

(3) MTTRs for the CH-54A components generally increased over the period 1969-72; however, as discussed under the OH-58A (above), this apparent trend does not necessarily indicate a true increase in MTBR (Figure 12).

(4) Trends for several engines show a definite improvement in unscheduled engine-removal rates (Figure 64).

(5) MTBRs generally increased for successive models of the T53 engine (Figure 69). However, MTBRs remained

approximately constant for the T-55-L-7/7B/7C engines (Figures 71 and 72).

(6) Unscheduled removal rates improved for all four CH-47 transmissions; average $\alpha = 0.22$ (Vol. 2, Part A, Table 8, p. BV-118).

(7) Unscheduled removal rates were generally constant for eight CH-47 major components (Vol. 2, Part A, Table 11, p. BV-145).

(8) On average, unscheduled removal rates worsened slightly for five CH-46 major components (Vol. 2, Part A, Table 13, p. BV-157).

(9) TBOs for transmissions and other components of the CH-47 generally increased (Figures 75-78).

(10) Component removal rates for the OH-6A improved, from 100 to 27,000 flight-hours; the maximum α that could be ascribed to these data is 0.26 (Figure 82).

(11) TBOs for UH-1A and H-13 both show good growth (Figure 83).

(12) MTBRs for the CH-54A/B generally improved (Table 46).

(13) MTBRs improved in 13 of 14 major components of the CH-53; average $\alpha = 0.23$ (Table 47).

(14) TBOs for the CH-54A/B generally improved (Table 46).

General Conclusions. MTBRs generally improved; they appeared to worsen in only two of the 10 programs for which data were obtained. Since overhauls are generally quite expensive, there is a strong motivation to incorporate improvements that will increase MTBRs. On the other hand, the increases in power and weight that usually take place in model changes over the life of a program tend to reduce MTBRs. TBOs almost always increased. TBOs are established mainly to protect against wearout-type failures in critical components. As flight experience is accumulated, it is normal to increase TBO after a component proves to be safe at the previous TBO. However, TBOs are sometimes lowered--due to the power and weight increases noted above.

C. MISHAP RATES

There are different categories of mishaps, but in general they cover all incidents of a dangerous or potentially dangerous

character--from minor incidents (such as precautionary landings) to major accidents (in which an aircraft is heavily damaged or lost). Chapter II includes time-series plots for four categories of mishaps:

- Total mishaps
- Mishaps involving materiel failure
- Total major accidents
- Major accidents involving materiel failure.

The following data on mishaps are presented in this study:

(1) Army mishap rates (both total and those involving materiel failure) tended to increase (Figure 38).

(2) Navy mishap rates (both total and those involving materiel failure) tended to increase (Figure 39).

(3) Army accident rates (both total and those involving materiel failure) tended to decrease (Figure 38).

(4) Navy accident rates (both total and those involving materiel failure) tended to decrease (Figure 39).

(5) Fifteen of 17 helicopter types showed decreasing major-accident rates. Average α for all 17 types was 0.23 (Vol. 2, Part A, Table 4, p. BV-65).

General Conclusions. Total mishap rates tend to increase, while major accident rates tend to decrease. Evidently, the more serious types of failures (those causing accidents) tend to be corrected, while minor problems are let go. The increasing mishap rate is probably due to the factors noted in discussing increasing failure rates (last sentence of Section A, above).

D. MAINTENANCE-ACTION RATES

Maintenance actions are those actions necessary for retaining an item in (or restoring it to) a specified condition. Maintenance-action rates tend to follow failure rates (i.e., if failures increase, maintenance actions tend to increase). As in the case of failures, maintenance actions can be expressed either as a rate per flight-hour or as a mean time between maintenance actions

(MTBMA). We recommend that maintenance actions be reported as MTBMA, since this format is directly comparable to our recommended reporting of MTBF. The following data involving maintenance-action rates are presented in this study:

(1) Maintenance-action rates for individual CH-47A aircraft in Army service tended to increase (Figure 1).

(2) Maintenance-action rates for helicopters in Navy service tended to increase (MTBMA tended to decrease--Figures 14, 17, 20, 23, 26, 29, 32, and 35).

General Conclusions. Maintenance-action rates tend to worsen in field service. This result is compatible with the finding of increasing failure rates in field service.

E. OPERATIONAL AVAILABILITY

Operational availability is the percent of aircraft that are available for flying in an operational unit. It reflects all previous mission-aborting failures that have not yet been repaired. As such, it depends not only on the intrinsic R&M characteristics of the aircraft but also on the level of maintenance personnel, equipment, and spare parts available to maintain and repair the aircraft. Hence, operational availability is an imperfect measure of R&M characteristics; nevertheless, differences in R&M characteristics are generally reflected in operational-availability rates. The following data on operational availability are presented in this study:

(1) The operational availability of the UH-1D increased over its first three years of Army Service (Figure 8).

(2) The operational availability of the AH-1G increased during its first half-year of Army service and then remained approximately constant (Figure 8).

(3) Operational availability of the CH-54A increased initially and then remained approximately constant. For the CH-54B, it increased initially and then remained approximately constant, at about the same rate as for the CH-54A (Table 43).

General Conclusions. Operational availability tends to increase over the first year or so of field service and then to remain approximately constant. The initial increase is probably due more to learning by operating and maintenance personnel and the increased availability of equipment and spare parts than it is to improvement in R&M characteristics per se.

F. MAINTENANCE MAN-HOURS

Maintenance man-hours required to maintain the aircraft are usually expressed as a rate per flight-hour (MMH/FH). The following MMH/FH data are presented in this study:

(1) MMH/FH increased for individual CH-47A aircraft in Army service (Figure 1).

(2) MMH/FH of the UH-1D decreased over its first three years of Army service (Figure 7).

(3) MMH/FH of the AH-1G decreased during its first half-year of Army service and then remained approximately constant (Figure 7).

(4) For all Army helicopters, MMH/FH tended to remain constant over time; if MMH/FH changed, it tended to worsen more often than it improved (Table 6).

(5) For all Navy helicopters, MMH/FH tended to worsen (Figures 16, 19, 22, 25, 28, 31, 34, and 37).

(6) For all Air Force helicopters, MMH/FH tended to worsen over time (Table 16).

(7) MMH/FH decreased for successive models of the T53 engine (Figure 68).

(8) MMH/FH for the CH-47 decreased from 1965 to 1967 and then remained approximately constant through 1972 (Vol. 2, Part A, Table 1, p. BV-4).

(9) MMH/FH for the CH-46 remained approximately constant ($\alpha = 0.01$--Vol. 2, Part A, Table 7, p. BV-116).

(10) MMH/FH for the H-21 increased for about the first year of service in the French Army and then remained approximately constant (Vol. 2, Part A, Figure 91, p. BV-117).

(11) For equal weight empty, MMH/FH has been decreasing with year of introduction into service of new designs (Vol. 2, Part A, Figure 128, p. BV-160).

(12) MMH/FH for the CH-54A and CH-54B were approximately constant; however, MMH/FH were higher for the CH-54B than for the CH-54A (Table 43).

General Conclusions. During the first year or so of service, MMH/FH tends to vary--increasing in some cases and decreasing in others. During the mature portion of service life, MMH/FH tends to remain constant or increase slightly. The factors noted in discussing increasing failure rates (last sentence of Section A, above) tend to increase MMH/FH. On the other hand, design improvements (and learning by operating and maintenance personnel) tend to decrease MMH/FH. Evidently, these factors tend to offset each other.

We expect that the patterns of reliability growth (degradation) of future helicopter programs will be similar to those of the past programs presented herein. Though there is probably more management emphasis on reliability now than there was in the past, the maturing of helicopter technology tends to make improvements in reliability more and more difficult to achieve over time. Hence, though the initial levels of reliability in future helicopter programs will probably be improved over those of past programs, the subsequent rates of improvement from these initial levels will probably be similar to those of past programs. Assuming that reliability growth (degradation) of future helicopter programs will be similar to those of past programs, we would expect:

- Failure rates (both total and mission-aborting) will definitely improve during the development phase of the program; following introduction into field service, they will probably worsen slightly.
- MTBRs and TBOs of components will increase in most cases--both during development and in field service.
- Mishap rates will probably increase during field service; accident rates will very likely decrease during field service.

- Maintenance-action rates will probably worsen during field service.
- Operational availability will probably increase over the first year or so of field service and then remain approximately constant.
- MMH/FH will probably vary somewhat during the first year of field service and thereafter remain approximately constant or increase slightly.

We would like to make two recommendations regarding the reporting of R&M data:

(1) The Services all employ 100 percent reporting of helicopter R&M data; the result is a massive quantity of inaccurate and incomplete data on every Service helicopter. Many of the data are needed for other purposes (e.g., the maintenance log for an aircraft and the inventory control of serial-number components). However, for the collection of the type of R&D data presented above, *we recommend the use of a sampling reporting system wherein high-quality data on relatively few helicopters are reported.* This recommendation is especially urged on the Army, because it operates approximately 8,700 of the total of about 10,200 U.S. military helicopters. This recommended change should increase the quality of the R&M data systems.

(2) R&M contractual arrangements provide for the deduction of failures that are judged to be due to causes other than the mechanical performance of the helicopter itself. In addition, failures for which a "fix" has been developed may be deducted, even though in some cases the "fix" has not been tested. This deduction procedure can lead to optimistic reliability projections. For example, in the AH-56A program, Lockheed was allowed to deduct 1,487 of 1,770 failures; as a result, they were able to show a system reliability of 0.701 for a 2.5-hour mission, while our calculations indicate that the system reliability actually achieved was 0.100. *We recommend that the Services be much less permissive in allowing contractors to deduct failures; otherwise, unrealistically optimistic projections of reliability will result with a high price to the user when the helicopter enters field service.*

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FIGURES

TABLES

PREFACE

This study was prepared by the Institute for Defense Analyses for the Office of the Director of Defense Research and Engineering (Tactical Warfare Programs) under Task Order T-105 with the Defense Advanced Research Projects Agency. The study was under the technical direction of Mr. John W. Klotz, Assistant Director (Combat Support) of the Tactical Warfare Programs Office.

Because of the difficulties encountered in locating and obtaining helicopter-reliability data, it was felt that the usefulness of this report would be increased if many of the data were included so that the report could be used as a source of data by analysts; as a result, the report is more voluminous than would otherwise be warranted for use by more senior managers.

The study was restricted by the availability of helicopter-reliability and maintainability (R&M) data. All U.S. helicopter manufacturers were asked for data; data were obtained under subcontracts with Boeing Vertol, Hughes, and Sikorsky. In addition, data were obtained from various service organizations. In spite of this rather exhaustive data-collecting effort, the amount and quality of data obtained were somewhat disappointing. There were two basic reasons for the data problem: (1) most of the helicopters were developed fifteen years ago or more, and R&M data collection was not emphasized in those days; (2) the retrieval of data was difficult because much of it has been lost with the passage of time. The lack of data was particularly serious in the pre-service development phase of the helicopter programs. Moderately good pre-service data were obtained only for the AH-56A, OH-6A, and CH-53 programs.

Because of the data problem, it was not feasible to accomplish some of the objectives of the task order. For example, the data were generally so crude that it was not practical to calculate confidence limits; in many cases, we simply observed whether R&M characteristics were improving, remaining constant, or worsening over time.

Chapter I

SERVICE RELIABILITY/MAINTAINABILITY (R/M) DATA

A. ARMY DATA

Army aircraft reliability/maintainability (R/M) data are reported under The Army Maintenance Management System (TAMMS). This is a 100-percent reporting system based on a written description of every maintenance action on every Army aircraft. Analysis of these data requires extensive hand and computer editing procedures that have been developed by the Army Aviation Systems Command (AVSCOM), St. Louis, Missouri.

During a visit to AVSCOM, we obtained the reports (in computer printout form) on eight CH-47A aircraft. IDA personnel analyzed the printouts by hand. The effort required by this limited analysis proved that, within the time and manpower constraints of this study, it would be completely beyond IDA's capability to analyze the Armv TAMMS data. However, AVSCOM has issued reports based on the TAMMS data for the following helicopters: the OH-58A, AH-1G, CH-54A, and CH-47A. From these reports, we have extracted data that show R/M trends over time, as well as R/M trends as a function of helicopter empty weight. From general Army regulations and field manuals, we have also extracted maintenance man-hour data, which are presented and analyzed below. We have also included some data (obtained from Bell Helicopter Company) for the OH-58A, AH-1G, and UH-1D helicopters in Army service.

1. Analysis of Field Data for the CH-47A

The data used in this analysis were supplied us by the Directorate for Product Assurance (AVSCOM). The data that we have analyzed are for the CH-47A helicopter and are output from the Reliability and Maintainability Management Improvement Techniques (RAMMIT) data processing system developed by AVSCOM.

The particular RAMMIT report that we have used is known as The Aircraft Life Cycle Maintenance and Ownership Record (TALCMOR). TALCMOR (see the output sample in Table 1) provides a chronological listing (starting with the acceptance of an aircraft into the Army inventory) comprised of all maintenance actions perf d on the aircraft, transfers of ownership, and scrappage or salvage actions that occur during the life cycle of the aircraft. These events are reconstructed from the Army TAMMS (Ref. [1]) records, which are transcribed on magnetic tape and stored in the AVSCOM RAMMIT data bank. This listing is available from AVSCOM on request for each serial-numbered aircraft in the Army inventory.

The following TAMMS forms are used to develop a TALCMOR listing:

(1) 2407 Maintenance Request
(2) 2408-3 Equipment Maintenance Record (Organizational)
(3) 2408-7 Equipment Transfer Record
(4) 2408-8 Equipment Acceptance and Registration Record
(5) 2408-9 Equipment Control Record.

The only 2407 records that are accepted into the chronological listing are those that record maintenance actions on the end-item aircraft. As of December 1969, DA Form 2408-3 has been deleted from TAMMS; and all organizational maintenance previously reported on Form 2408-3 is now reported on Form 2407. Also, as of November 1972, DA Forms 2408-7 (Equipment Transfer Record) and 2408-8 (Equipment Acceptance and Registration Record) were deleted in favor of one form, DA Form 2408-9 (Equipment Control Record).

Table 1. SAMPLE OF TALCMOR OUTPUT

FGCAQF A/C LIFE CYCLE LIST PAGE 13150 REC CD PALC

SERIAL NO	FSN	NOUN DESCRIPT	LINE NO	MOD/SER
6619266	1520633E836	HELTRANS	55003C	CH-47A

EQUIPMENT MAINTENANCE RECORD,2408-3

CONT #	UIC	EQUIP AVAIL	EQUIP SERV	TOOL AVAIL	GAL/PER	UTIL
V61112	WAAWAO	CC0 CCC				0

DATE	FLT HR	FAILURE DETECTED	FIRST INDICATION	ACTION	FAILURE	COMPONENT/PART NOUN/SERVICE	MAN HOUR	FSN PART	QTY
8173	00751	D NORM OPER	360 INTRMIT	A REPLACED	120 CHAFED	ELEM	1.5	1680B959427	001
8173	00751			E SERVICES		DI	6.C		000
8173	00751			F SERVICES		SERV	3.C		0C0
8174	00758			F SERVICES		CI	6.C		000
8174	00758			F SERVICES		SERV	2.C		000
8175	00758	F OTHER	C99 OTHER	A REPLACED	160 CONTACT/CONNECTION DEFECT	PACKING	C.5	533C5580364	001
8176	00758	D NORM OPER	068 INOPER	A REPLACED	070 BROKEN	CEN	C.5	662C5851503	001
8176	00758			E SERVICES		CI	4.C		000
8176	00758			E SERVICES		SERV	2.C		000
8178	00765			E SERVICES		DI	7.C		000
8178	00765			E SERVICES		SERV	3.C		000
8179	00765	D NORM OPER	C99 OTHER	A REPLACED	381 LEAKING	COOLER	2.5	1680B665999	001

MAINTENANCE REQUEST 2407,WORK REQUEST

CONT #	UTIL	UIC	FAILURE DETECTED	FIRST INDICATION	REPAIR UIC	TYPE CRC	DELAY DUETO	TOT MNHR	TOT MN HRCOST	TOT PART COST	DATE RECD	DATE STRT	DATE INSP	DATE ACPT	DISPC
PC2999	C	WAAWAC	D NORM OPER	C99 OTHER	WAGWAO	TCE		430.			8184	8186	8186	8186	A USE

DATE SUPM	FLT HR	ACTION	FAILURE	COMPONENT/PART NOUN/SERVICE	MAN HOUR	FSN PART	PART SCURC	QTY
8184	00775	A REPLACED	381 LEAKING	ENG TURB	4C.C	2840987971?	A ACR	000
8184	00775	F INIT INSP			1.C			000
8184	00775	G FINAL INSP			2.C			000

The records in the TAMMS data bank at AVSCOM are sorted to select the records mentioned in the preceding paragraph for each Type/Model/Series (TMS) fleet. They are then sorted again to arrange the records in chronological order for each end-item aircraft within a given TMS fleet. Thus, a TALCMOR report for a particular aircraft consists of all 2407, 2408-3, 2408-7, 2408-8, and 2408-9 records for that aircraft (arranged in chronological sequence).

a. Limitations and Weaknesses of TAMMS and TALCMOR Data for Measuring Reliability

The accuracy of a TALCMOR is, of necessity, limited to quality of ownership and maintenance reporting and accuracy of the keypunching required to get the data into the RAMMIT data processing system. The TALCMOR reports that we have examined gererally contain many time gaps in the reporting of maintenance on the Forms 2407 and 2408-3. Moreover, these TALCMOR reports contain (1) many records that are out of chronological order (usually because of keypunching errors), (2) duplicate records that report the same maintenance, and (3) records that report maintenance but omit maintenance man-hours and part numbers. Thus, it was necessary for us to spend considerable time and effort to edit and assemble the data into a useful format.

For the purpose of measuring the field reliability of Army helicopters, the TALCMOR data are probably the best that are available from the Army. However, the TAMMS data system is not reliability-oriented in the first place--a fact that severely limits the usefulness of TAMMS as a source of reliability data. There are several reasons for this:

(1) It is difficult to determine the occurrence of failures by examination of either the 2408-3 or 2407 forms. These forms contain failure codes, when-failure-detected codes, first-indication-of-trouble codes, and action codes [1, Appendix A, Tables A-1 - A-5]. In practice, however, only

the failure and action codes are recorded by the maintenance personnel who prepare the Forms 2407 and 2408-3; and the failure codes are generally insufficient to determine the degree of malfunction. It is altogether impossible to determine whether the reported event aborted a mission.

(2) TAMMS is a 100-percent reporting system. Forms 2407 and 2408-3 are completed for every helicopter in the Army inventory. The result is a massive amount of low-quality data for the entire fleet of Army helicopters. Once assembled, and even with the help of the largest computers, this volume of data is far too great and unwieldy to be processed efficiently.

(3) Part numbers are generally omitted from the forms unless a component is being replaced. Thus, the reliability data contained in a TALCMOR report cannot be further subdivided by component or subsystem. Therefore, it is not possible to determine accurately the reliability or failure rates of individual components in a given TMS fleet. For this reason, our reliability estimates are limited to the complete helicopter. We remark, however, that removal rates for major components are available in the RAMMIT Major Items Removal Frequency (MIRF) report.

(4) In many cases, the removal and installation of selected aircraft items is not reported on Forms 2407 and 2408-3. Most of these maintenance actions, especially those involving major high-cost or maintenance items, are reported on DA Form 2410 (Component Removal and Repair/Overhaul Record). This form is used to record removal, overhaul, and reinstallation activity for a specific serial-number component, and it stays with that component. Form 2410 shows the serial numbers of both the aircraft from which the component is removed and the aircraft on wich the component is installed. Thus, the 2410 forms are specific to individual serial-number components rather than to serial-number aircraft; and, for this reason, they are not included in a TALCMOR report for an individual aircraft. For example, an engine may be removed from one aircraft, overhauled, and then reinstalled on a different aircraft. This complete series of actions is reported on different copies of the same Form 2410. In order to make use of this information, AVSCOM publishes the Major Items Removal Frequency (MIRF) report for high-cost items on each type of Army helicopter. This report is part of the output from the RAMMIT system.

(5) Lost TAMMS records impair the usefulness of a TALCMOR report for measuring reliability. All the CH-47A TALCMOR reports that we have examined contain gaps in the reporting of maintenance and of failures. Thus, because of missing data, it is not possible to obtain accurate reliability estimates. In some cases for an end-item aircraft, there are as many as 1,000 flight-hours for which there is no man-hour or failure accounting.

(6) Time intervals between successive failures on an end-item aircraft cannot be determined accurately from a TALCMOR report. Forms 2407 and 2408-3 contain the cumulative flight-hours on the end-item aircraft at the time the maintenance action recorded on the form is performed. Thus, to obtain the time interval between successive failures, it is necessary to compare successive records--which cannot be done when there are missing data. Also, it is common practice to neglect many minor failures and repair them at the 100-hour Preventive Maintenance Periodic (PMP) inspection. Thus, failures tend to accumulate sharply near every 100-hour checkpoint. The actual failure rate probably does not exhibit these cyclical peaks.

b. Recommendations

The TAMMS reporting system as presently structured is adequate for reporting man-hours expended in maintenance on Army aircraft. However, the data gathered are inadequate for tracking the field reliability of Army helicopters. We make several recommendations, which (if implemented) would allow accurate field reliability data to be obtained through the TAMMS reporting system:

(1) Detailed and accurate reliability data for a small sample of Army helicopters would allow a more reliable assessment of field reliability than does a massive quantity of inadequate, inaccurate, and incomplete data on every helicopter in the Army inventory. In this age of sophisticated statistical methodology, it is not necessary to do exhaustive sampling on a population in order to determine certain population characteristics. This is particularly true in the field of reliability measurement.

(2) In measuring reliability, we are interested in estimating the probability distribution (and its mean--MTBF) of the times to failure for a certain population of similar items. Thus, the logical data to be collected for the purpose of measuring the field reliability of helicopters concern failures--the time of occurrence of a failure, the time interval between successive failures, number of duty cycles since last failure, hours on a component at the time of failure, part number of failed component, etc. Thus, the TAMMS data forms--particularly DA Forms 2407 and 2410--should be revised so that this type of reliability data (in addition to maintenance man-hours) can be collected by the TAMMS system. The TAMMS system is the logical mechanism for collecting and reporting accurate field reliability data.

(3) The coding system used in TAMMS to record failures and maintenance actions is simple. Thus, it is easy for maintenance personnel to use the system. However, the TAMMS failure codes are not adequate for determining the occurrence of failures. At present, it is impossible to determine whether a failure is relevant to safety of flight or whether it caused a mission abort. If the TAMMS reporting system is expanded to include reliability data, the Army's failure definitions, failure codes, and action codes should be revised so that failures and the conditions surrounding their occurrence are accurately recorded on the TAMMS data forms. Thus, a revised TAMMS-failure coding system should distinguish between system, mission, and safety of flight failures.

Some simple trade-offs are involved in these recommendations, which are not, however, simple to implement. The revisions of TAMMS that we have proposed would undoubtedly make the system more costly and unwieldly than the present TAMMS if the revised system were applied to every helicopter in the Army inventory. However, by limiting this extended coverage to a much smaller sample of aircraft (10 percent or less of the Army helicopter inventory), the number of personnel and man-hours required to obtain accurate helicopter field reliability and maintainability

data could probably be substantially reduced.[1] To be sure, it would require greater training and motivation to obtain from maintenance personnel the increased performance that would be required to collect accurate and complete helicopter reliability data of the type we have discussed here. The personnel required to collect and codify the type of data sought in these recommendations would need specialized training in reliability, in order to be able to distinguish between the different types of failures. At present, people who are knowledgeable in reliability are not likely to be found at the organizational level filling out TAMMS forms.

c. Results

We have analyzed TALCMOR reports for a total of eight CH-47A aircraft. However, only five of these reports contained data that were complete enough for use in our study. The data presented and analyzed in this section are for the following sample of CH-47A aircraft: serial numbers 6507991, 6507994, 6508002, 6619068, and 6619071. These data cover more than 14,000 flight-hours on the CH-47A for the period March 1966 through March 1973. Table 2 shows maintenance man-hours per flight-hour (MMH/FH), maintenance actions per flight hour (MA/FH), and Failures/FH for the first 100 flight-hours, the next 400 flight-hours, and then for each 500-flight-hour interval to 2,500 flight-hours. The first five panels of the table present data for the five individual aircraft; the bottom panel presents the average R/M measures for the five aircraft. Each aircraft in the sample has accumulated flight-hours in excess of 2,500. The data in Table 2

[1]However, many of the data presently being collected are needed for other purposes (e.g., the maintenance log for an aircraft and the inventory control of serial-number components). Hence, a sampling program for all maintenance actions is not feasible; many would have to continue to be reported on a 100 percent basis.

Table 2. R/M MEASURES FOR THE ARMY CH-47A

R/M Measure	Number of Flight-Hours					
	100	500	1,000	1,500	2,000	2,500
Serial #6507991						
MMH/FH	16.46	12.25	9.19	22.05	18.35	16.61
MA/FH	0.98	0.74	0.45	0.35	1.00	1.08
Failures/FH	0.288	0.310	0.162	0.059	0.265	0.160
Flight-Hours with Data Missing	20	106	238	413	208	289
Julian Date	6159	7153	8100	9022	0041	0174
Serial #6507994						
MMH/FH	16.77	12.10	6.12	8.80	6.23	11.40
MA/FH	1.37	1.09	0.58	0.79	0.50	1.27
Failures/FH	0.286	0.391	0.250	0.196	0.150	0.390
Flight-Hours with Data Missing	16	82	136	182	121	102
Julian Date	6180	7193	8137	9071	9286	1210
Serial #6508002						
MMH/FH	13.76	14.83	11.22	6.41	18.43	12.96
MA/FH	0.65	0.68	0.67	0.51	1.59	2.06
Failures/FH	0.800	0.196	0.202	0.188	0.674	0.764
Flight-Hours with Data Missing	0	78	39	355	333	124
Julian Date	6202	7106	7333	8149	9334	1350
Serial #6619068						
MMH/FH	2.41	5.66	11.28	8.62	19.01	22.74
MA/FH	1.07	0.52	1.29	0.78	1.60	0.91
Failures/FH	0.267	0.119	0.161	0.192	0.423	0.167
Flight-Hours with Data Missing	78	138	114	102	262	265
Julian Date	7210	8030	9011	9242	0066	1139
Serial #6619071						
MMH/FH	7.64	7.64	37.73	45.70	58.78	15.36
MA/FH	0.54	0.65	1.11	1.38	1.48	1.75
Failures/FH	0.063	0.194	0.619	0.652	0.488	0.784
Flight-Hours with Data Missing	20	9	170	60	305	0
Julian Date	7177	7347	8214	9147	1130	3066
Average of Five Aircraft						
MMH/FH	11.41	10.50	15.11	18.32	24.16	15.81
MA/FH	0.92	0.74	0.82	0.76	1.23	1.41
Failures/FH	0.189	0.242	0.279	0.257	0.412	0.448

cover on-aircraft maintenance only for all levels of Army maintenance except depot maintenance.

In most cases, detailed examination of the R/M data revealed gaps in the reporting. These gaps are indicated in Table 2 by "Flight Hours with Data Missing." For example, Table 2 for aircraft #6507991 under 500 flight-hours shows 106 flight-hours with no maintenance data reporting--which means that, for the interval between 100 and 500 flight hours, we estimated that there were 106 flight-hours on this aircraft for which no failure or maintenance data were listed in the TALCMOR report. Since DA Forms 2407 and 2408-3 always show the cumulative flight-hours on the aircraft, we have an accurate record of cumulative flight-hours. However, there are days for which no maintenance action forms are listed in the TALCMOR report. Thus, the TALCMOR record for aircraft #6507991 shows a Form 2407 on Julian date 6223 (= 223rd day of 1966 = 11 August 1966), with 134 cumulative flight-hours. The next record in the report is a Form 2408-3 dated 6321 (98 days later, 17 November 1966), showing 156 cumulative flight-hours. It is very unlikely that this aircraft did not fly between 11 August 1966 and 16 November, say, and then was flown for (156 - 134 =) 22 hours on 17 November. Since CH-47A aircraft average about 2 hours of flying time each day, we can reasonably estimate that there are about 20 flight-hours in the time interval between 11 August and 17 November 1966 for which we have no reporting of maintenance actions. Since this aircraft averaged 0.74 maintenance actions per flight-hour during this period (100 to 500 cumulative hours), it is unlikely that it flew 22 hours with no maintenance actions. Hence, there are probably missing maintenance reports for this period.

In all cases, the three R/M measures of Table 2 have been corrected for the flight-hours with data missing. The corrections were made by eliminating the gaps in the data. For example, the three R/M measures for serial #6507991 between 100 and 500 flight-hours are based on the R/M activity levels during the (400 - 106 =)

294 flight-hours for which the data were believed to be completely reported.

The Julian dates for Table 2 show the dates on which the corresponding flight-hour milestones were reached (or the date on the maintenance form with cumulative flight-hours closest to the milestone). Thus, the 500-hour milestone for aircraft #6507991 was reached on Julian date 7153 (i.e., on the 153rd day of 1967). This date was 2 June 1967.

Figure 1 contains a semi-logarithmic plot of the three average R/M measures (from the bottom panel of Table 2) plotted versus flight-hours. The averages are plotted at the midpoint of each flight-hour interval. Thus, for the interval 100 to 500 flight-hours, we show the average of 0.242 Failures/FH plotted at 300 flight-hours, etc.

Figure 1 indicates that the trends of the three R/M measures all worsened as the helicopters accumulated flight-hours. The Julian dates of Table 2 indicate that it took an average of approximately five years for each helicopter to accumulate 2,500 flight-hours. The R/M averages for this group of five helicopters indicate that over this period of time the effect of any design improvements incorporated in the helicopters was more than offset by the aging of the helicopters--and possibly by the installation of additional equipment and accompanying weight growth. Army personnel suggested that another reason for the decrease in reliability with time might be that, as the helicopter operators become more familiar with the aircraft and develop more confidence in them, there is the possibility that they fly them harder and carry greater loads than they were designed for. In any case, the detailed R/M data for these CH-47A helicopters would indicate that *individual* aircraft do not experience R/M growth during their service life. It is possible, however, that later CH-47 models entering service in the 1970s might exhibit improved R/M characteristics at numbers of flight-hours equivalent to those of these CH-47s that entered service about 1966.

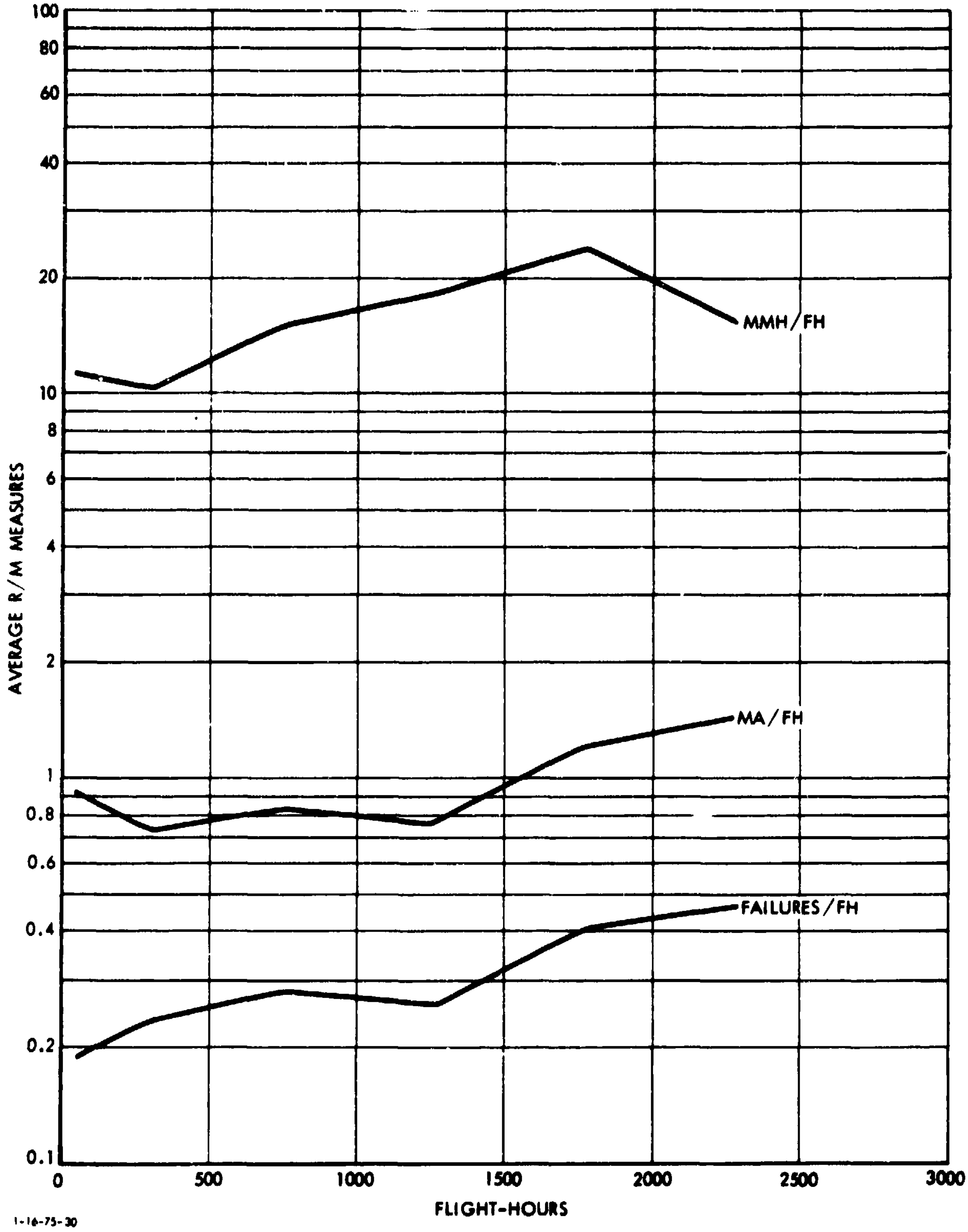


Figure 1. AVERAGE R/M MEASURES VERSUS FLIGHT-HOURS FOR THE ARMY CH-47A

2. Mean Time Between Maintenance Actions (MTBMA), Replace Actions, and Repair Actions

Table 3 presents data for mean time between (1) maintenance actions, (2) replace actions, and (3) repair actions for four types of Army helicopters. These are the only helicopters for which these data have been published by AVSCOM. These various mean times between actions have been plotted versus empty weight[1] in Figure 2. In all three types of actions, the mean time between actions (MTBA) is much lower for the CH-47A than for the CH-54A, even though the empty weight of both aircraft is nearly the same. Trend curves have been drawn between these points. These curves indicate a strong decrease in MTBA versus empty weight. These curves appear to be logical, since larger helicopters have more parts and should therefore be expected to require more MA/FH (or less MTBA) than smaller helicopters.

Table 3. ARMY HELICOPTER RELIABILITY DATA

Mean Time Between--	OH-58A	AH-1G	CH-54A	CH-47A
Maintenance Actions	1.7	1.3	0.73	0.45
Replace Actions	13.2	3.9	2.4	1.0
Repair Actions	75.0	45.0	18.9	4.4
Source: References [2], [3], [4], and [5].				

A word of caution concerning the averages presented in Table 2 is needed. These averages are for entire fleets of Army helicopters for specific time periods. The TALCMOR analysis for the CH-47A (above) shows, though inconclusively, that the various failure and maintenance rates for individual helicopters increase

[1]Army fleet average empty weights (in pounds) are as follows:

UH-1	4,700	CH-47	19,400
AH-1	5,300	CH-54	19,200
OH-6A	1,200	OH-58	1,500
CH-37	19,700		

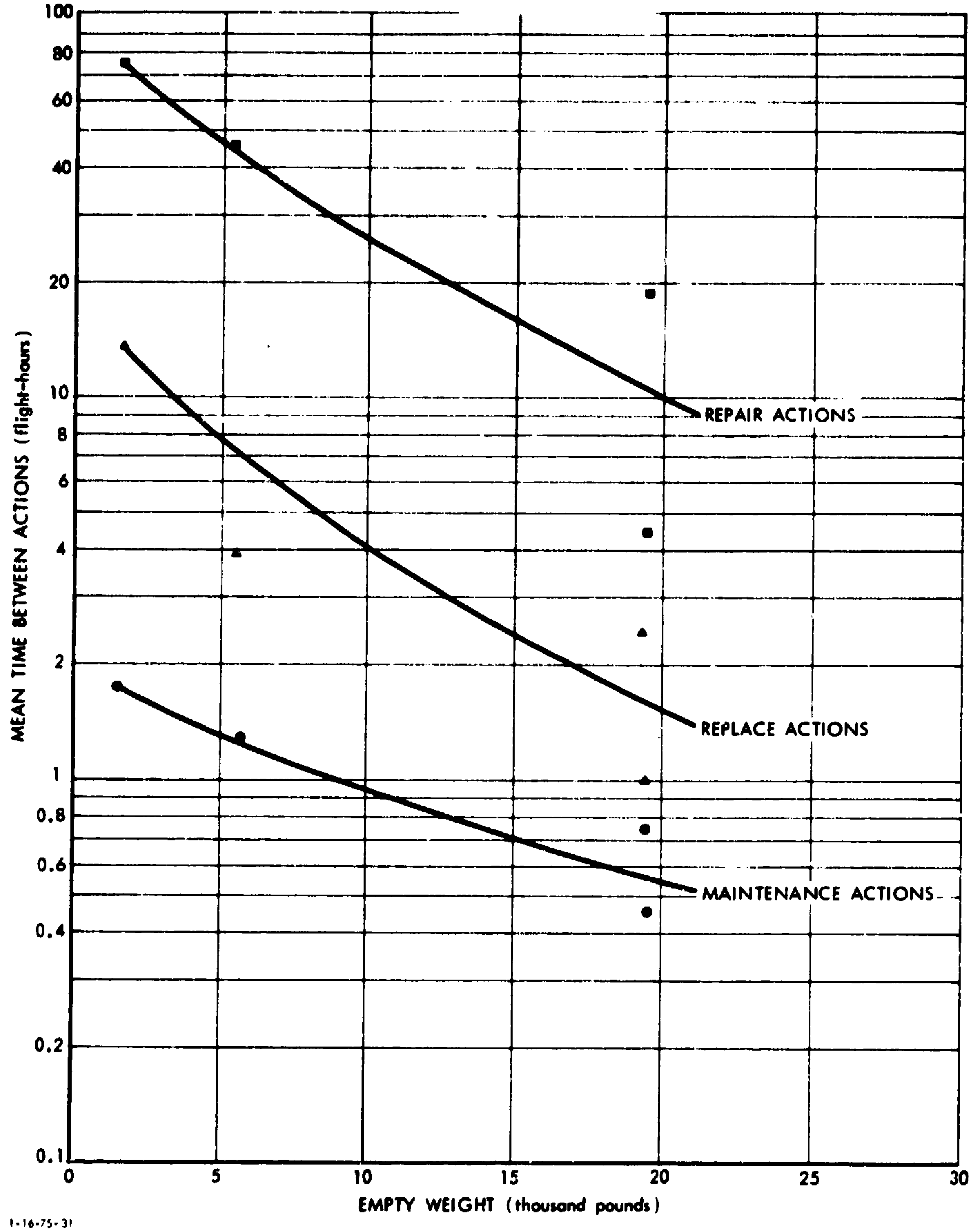


Figure 2. MEAN TIME BETWEEN ACTIONS VERSUS EMPTY WEIGHT FOR ARMY HELICOPTERS

with cumulative flight-hours. Thus, the values of Table 2 would tend to worsen as the fleets age. Since the average age of the OH-58A aircraft, for example, is less than that of the CH-54A aircraft, some of the reliability advantage of the OH-58A may be due to a lower fleet age rather than to smaller size only (as suggested by Figure 1).

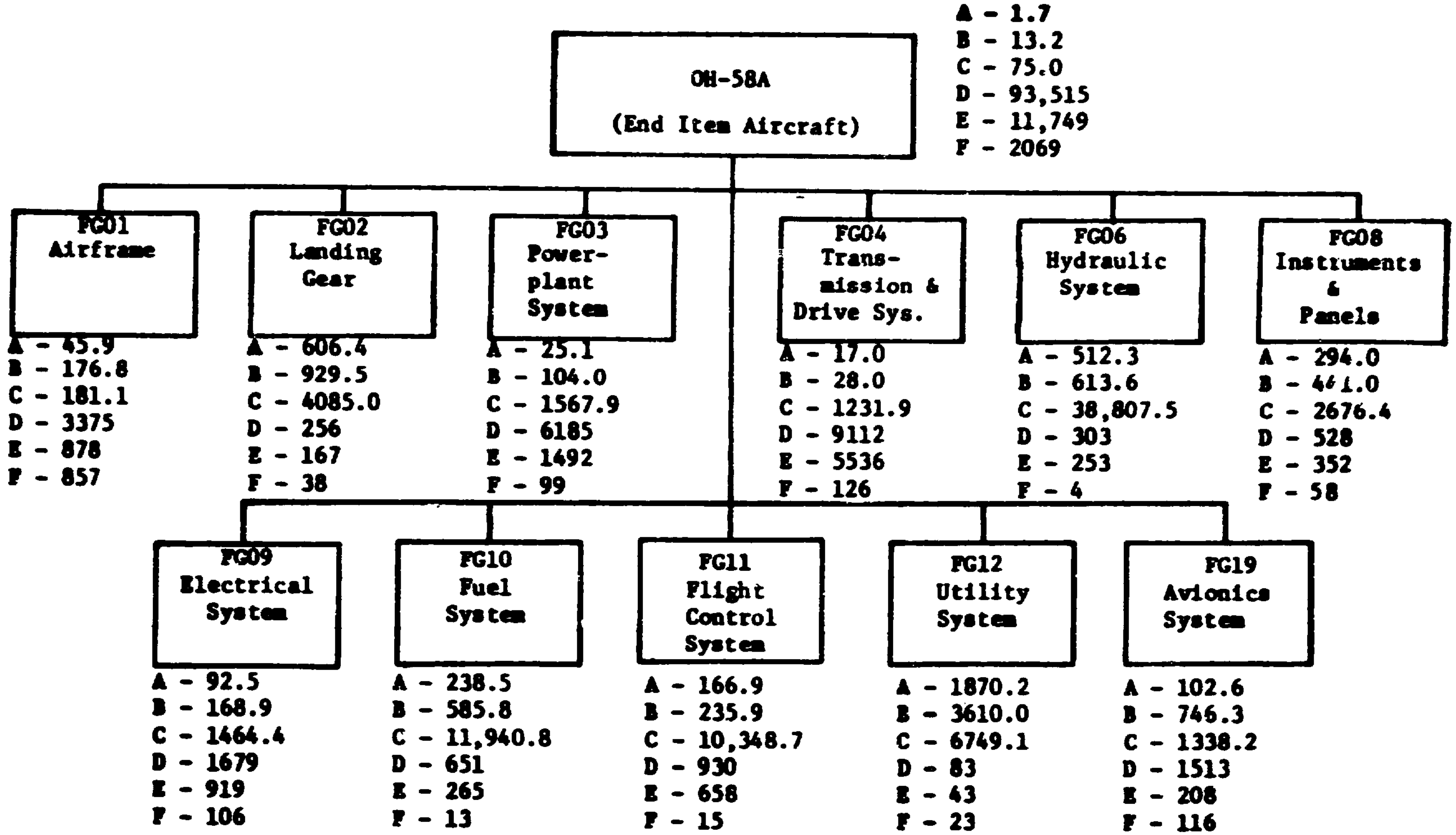
Figures 3a-c (reproduced directly from AVSCOM reports) show the breakdown of maintenance actions by functional group for the OH-58A, AH-1G, and CH-54A.

3. The OH-58A

The Army OH-58A was developed by Bell Helicopter from the OH-4A and Jet Ranger 206A. The OH-4A was Bell's entry in the Army Light Observation Helicopter (LOH) competition in the early 1960s. When that competition was won by the Hughes OH-6A, Bell developed the Jet Ranger from the OH-4A and sold it to commercial operators and foreign governments. In FY 1968, Bell sold to the Army and to the Navy versions of the Jet Ranger (the OH-58 and the TH-57, resp.). These aircraft entered service in calendar year (CY) 1969. This family of helicopters had accumulated roughly 200,000 flight-hours by the time the OH-58A entered Army service; hence, the initial reliability growth period (if any) would not be captured by the Army experience.

Figure 4 shows MTBF over a 15-month period during R&M demonstration at Fort Rucker. The MTBF was relatively high initially (probably reflecting the fact that the aircraft were new), but dropped during the first three months to a level that stayed fairly constant for the remainder of the program.

Figure 5 (from an AVSCOM report) covers a later period and shows MTB Aborts (rather than MTBF, as in the case of Figure 4) for each calendar quarter beginning in the third of 1970 through the second of 1972. Figure 5 indicates that MTB Aborts worsened somewhat over the period covered--due probably to the aging of the fleet.



A - Mean Time Between Maintenance Actions
B - Mean Time Between Replace Actions
C - Mean Time Between Repair Actions

D - Sample Size of Total Maintenance Actions
E - Sample Size of Total Replace Maintenance Actions
F - Sample Size of Total Repair Maintenance Actions

Source: Reference [2, p. 117].

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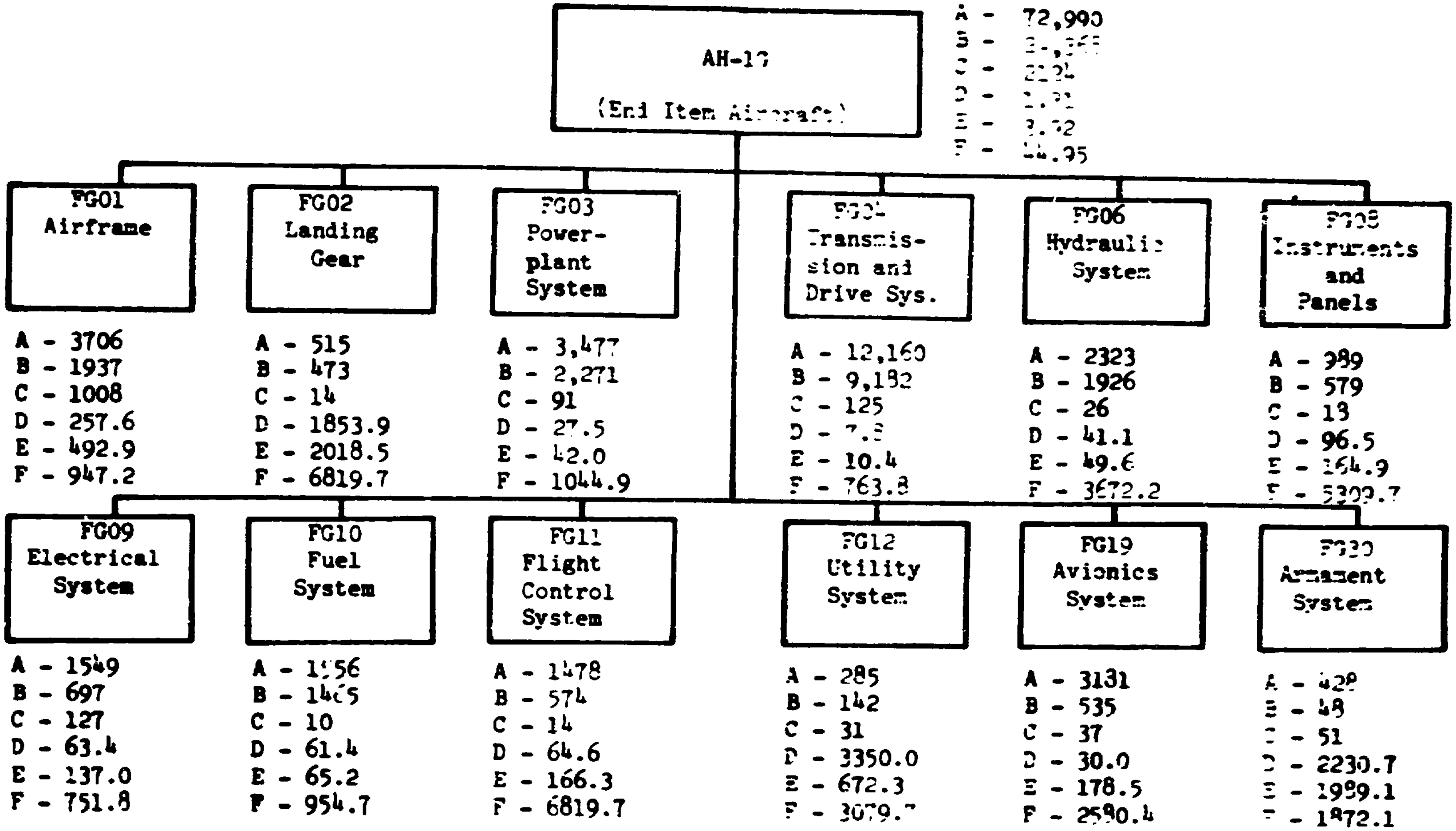
Figure 3. END-ITEM AIRCRAFT AND FUNCTIONAL GROUP-LEVEL BREAKDOWN OF MAINTENANCE ACTIONS
a. FOR THE ARMY OH-58A, 1 JANUARY 1970 - 30 JUNE 1971



A - Total Maintenance Actions
B - Total Replace Actions
C - Total Repair Actions

D - Mean Time Between Maintenance Actions
E - Mean Time Between Replace Actions
F - Mean Time Between Repair Actions

Source: Reference [3, p. 95]

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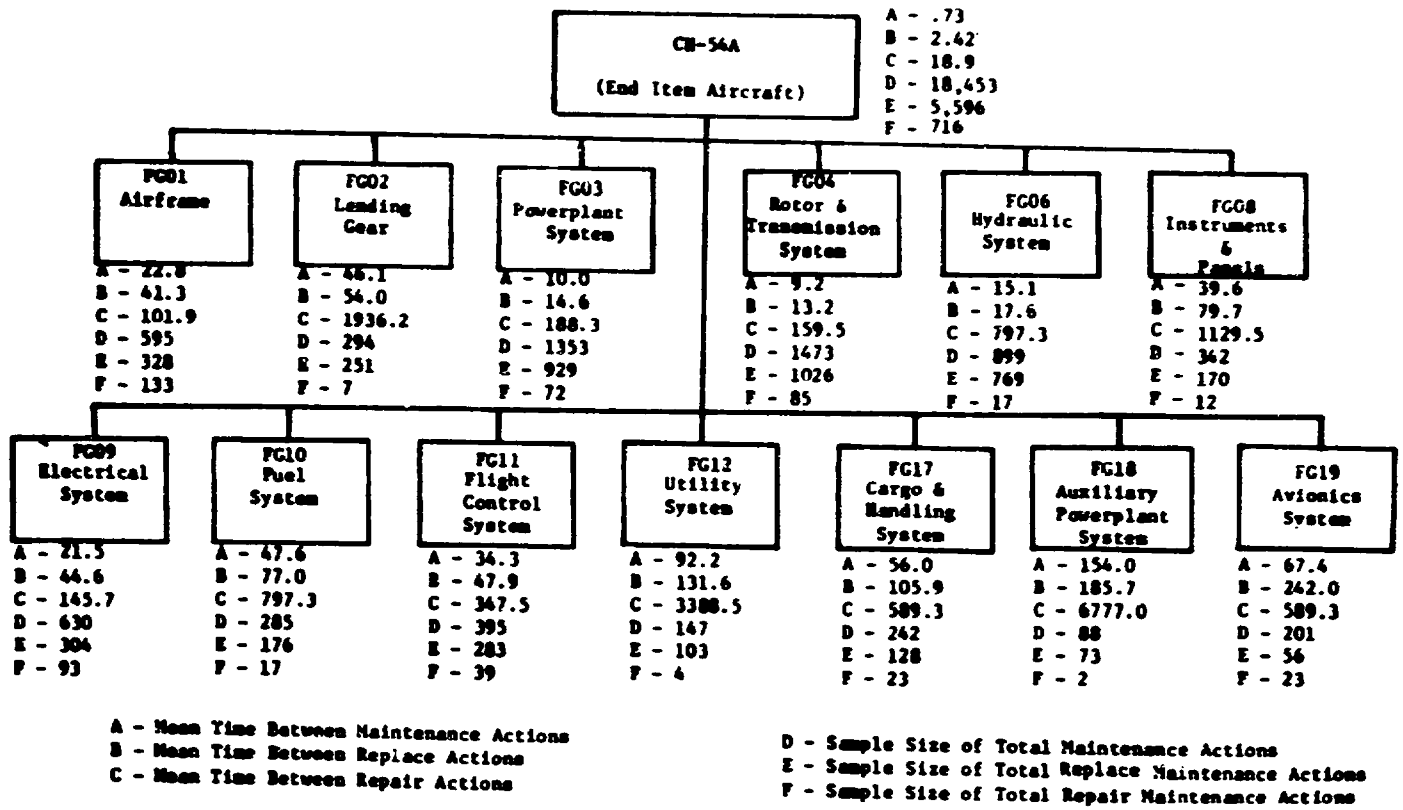
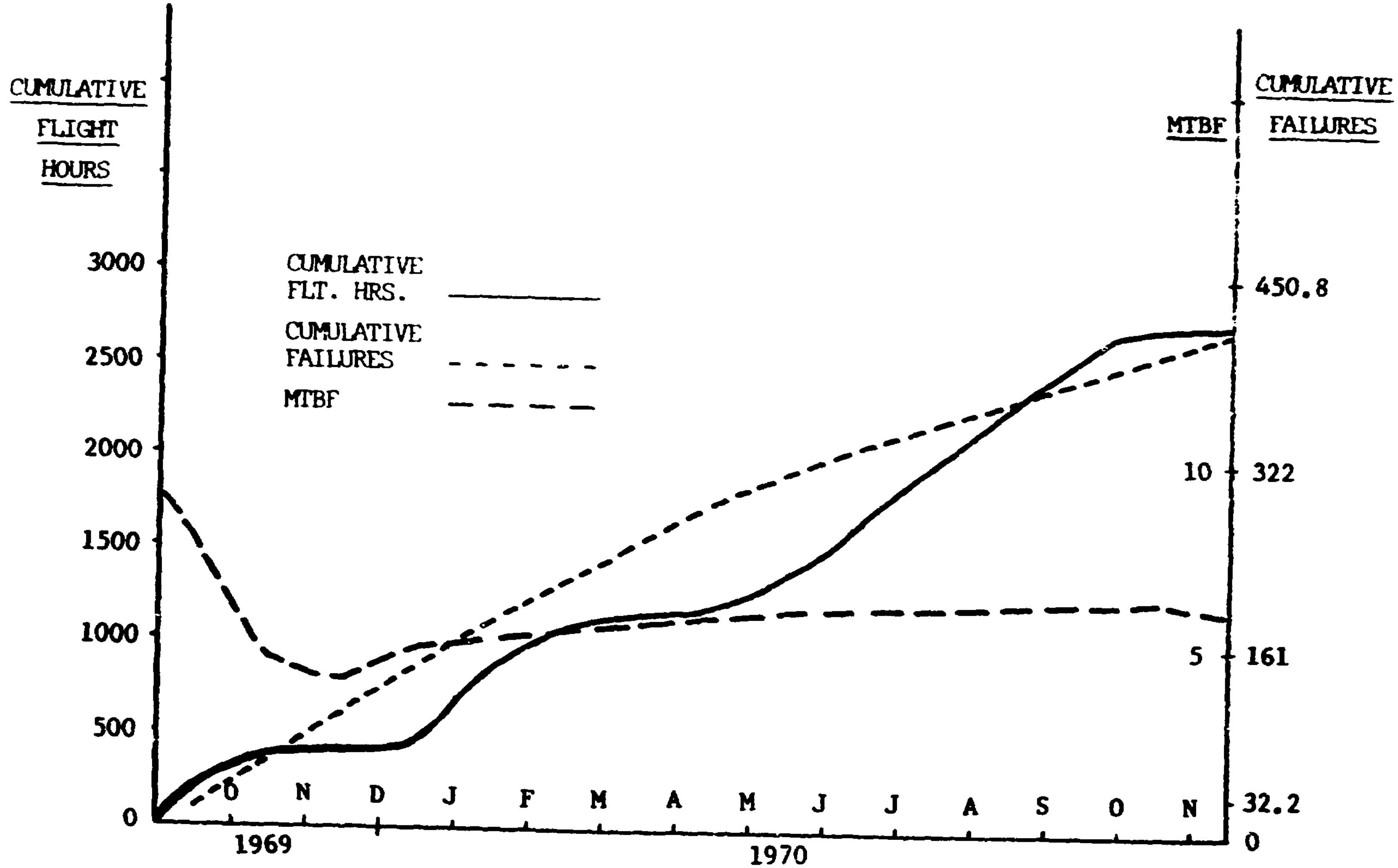
Figure 3 (continued)
b. FOR THE ARMY AH-1G, 1 JULY 1970 - 31 DECEMBER 1970



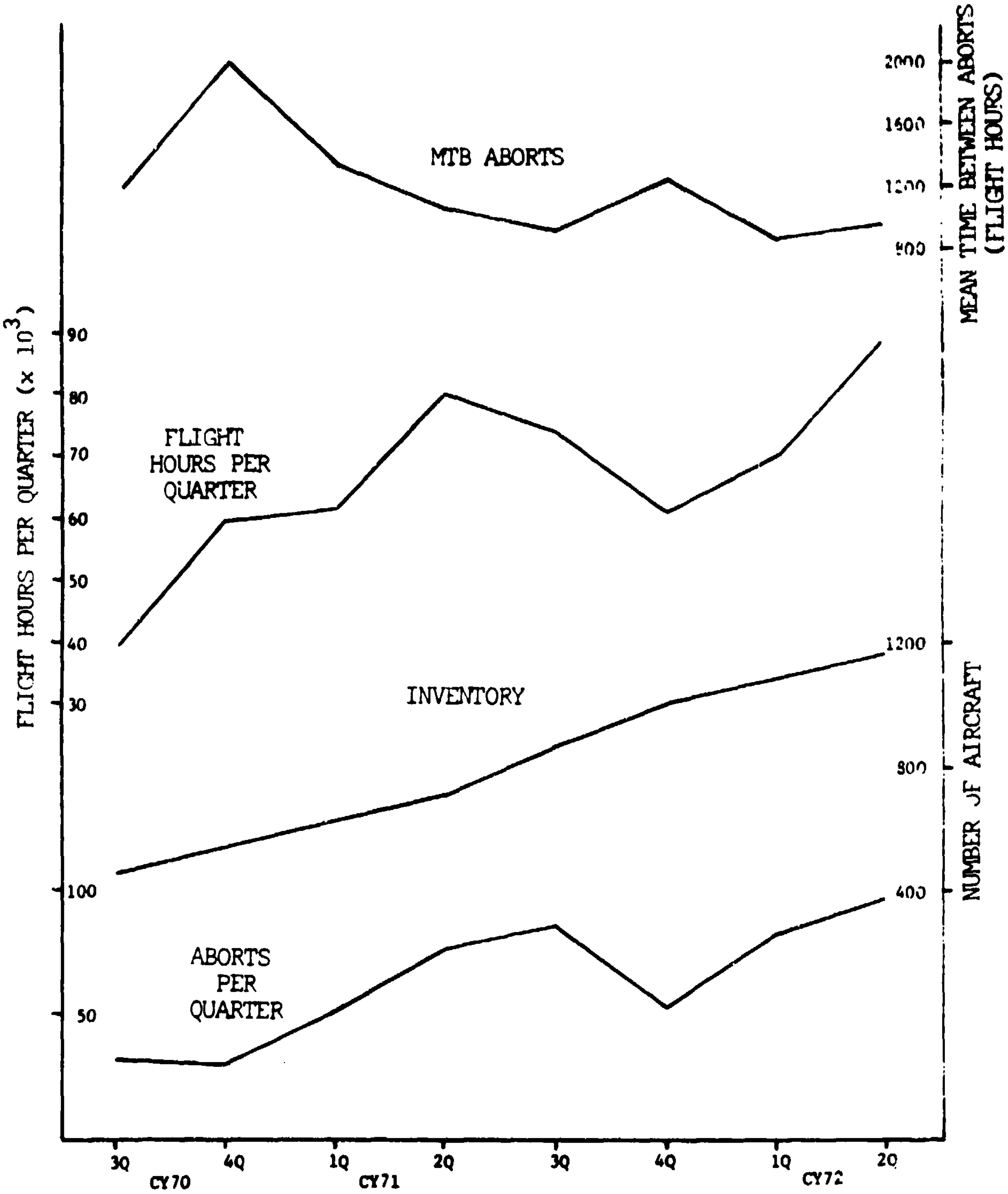
Source: Reference [4, p. 10].

Figure 3 (concluded)
c. FOR THE ARMY CH-54A, 1 JULY 1970 - 31 DECEMBER 1972



Source: Bell Helicopter Company.

Figure 4. R/M DEMONSTRATION AT FORT RUCKER FOR THE ARMY OH-58A



Source: Reference [2, p. 88].

Figure 5. GRAPHICAL SUMMARY OF SIGNIFICANT DATA FOR THE ARMY OH-58A

Figure 6 (from the same AVSCOM report) shows the trends in mean time to removal (MTTR) for major items of the OH-58A. The various panels of Figure 6 cover 21 items; by visual inspection, the trends were categorized as follows:

MTTR increased:	16
MTTR remained constant:	3
MTTR decreased:	2

The categorization is noted to the right of each trend by the words *up*, *constant*, or *down*. The relatively greater number of increasing MTTRs would seem to indicate that the helicopter as a whole experienced reliability growth in MTTR over this period of time. However, closer examination of the data for the OH-58A fleet yields a different interpretation. For example, in Figure 6 the freewheeling unit, PN 20604023013, exhibits a sharp upward trend in MTTR from the fourth calendar quarter of 1969 through the second of 1972--going from about 125 hours MTTR to more than 800 hours MTTR. In fact, during this 11-quarter period there were seven quarters when MTTR exceeded 550 hours, four quarters when MTTR was less than 475 hours, and two quarters when MTTR was less than 300 hours.

However, the first OH-58A aircraft were delivered to the Army in May 1969, and at the end of the fourth calendar quarter of 1969 only 99 of these aircraft had been accepted into the Army inventory. As of September 1972, the aircraft in the Army's OH-58A fleet had averaged 32.4 flight-hours per month per aircraft. Thus, by the end of CY 1969 very few OH-58A aircraft would have accumulated more than 200 flight-hours. Thus, MTTR for any OH-58A components in CY 1969 would have to be less than 200 hours. An examination of the trends in Figure 6 shows that, for every part number where there is a point plotted for the fourth calendar quarter of 1969, the MTTR is less than 150 hours. Thus, all these upward trends are rather doubtful. In fact, as of 30 September 1972, only 25 percent of the OH-58A fleet had accumulated more than 526 flight-hours.

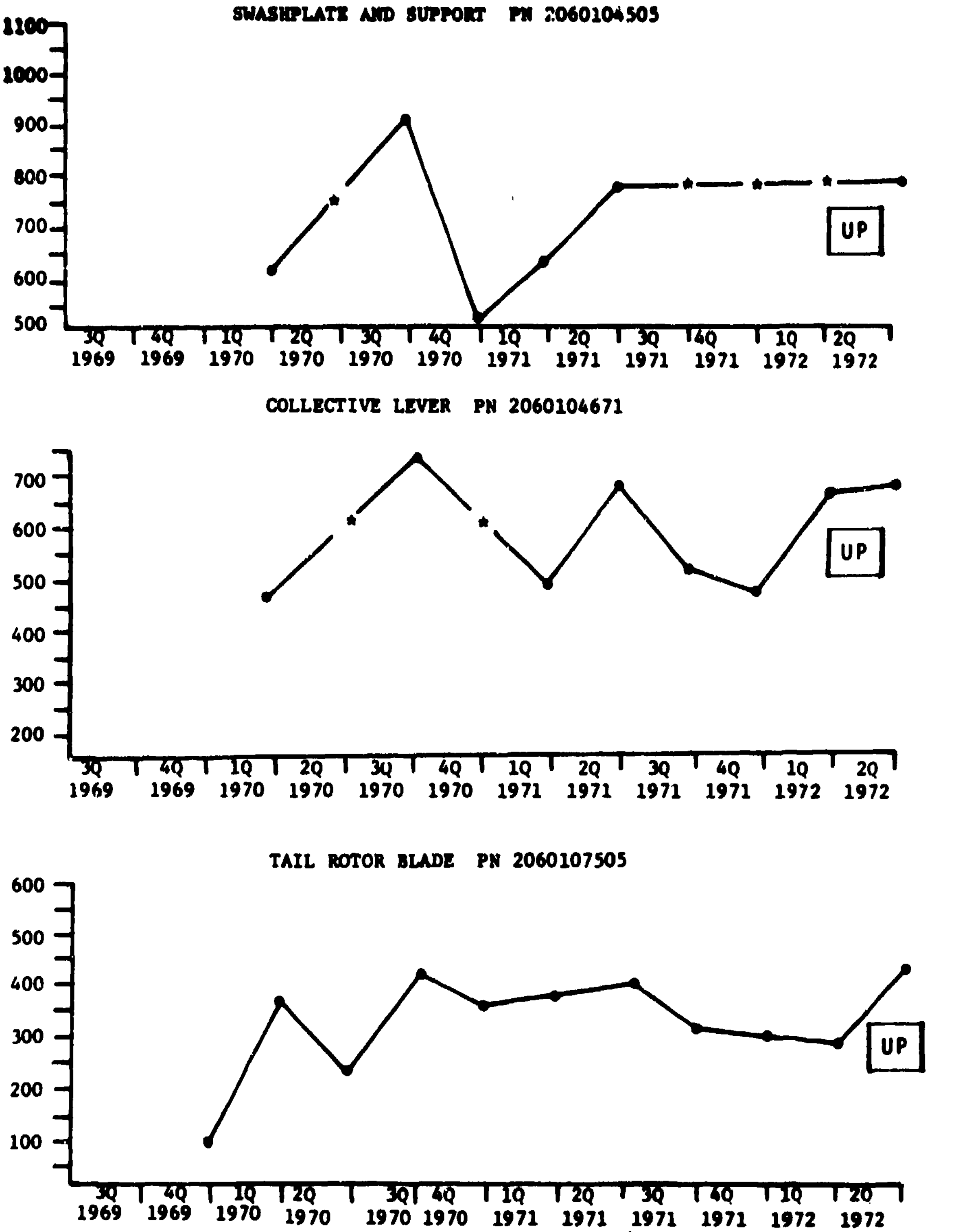


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Figure 6. MEAN TIME TO REMOVAL (MTTR) TRENDS FOR THE ARMY OH-58A, 1 JULY 1969 - 30 JUNE 1972

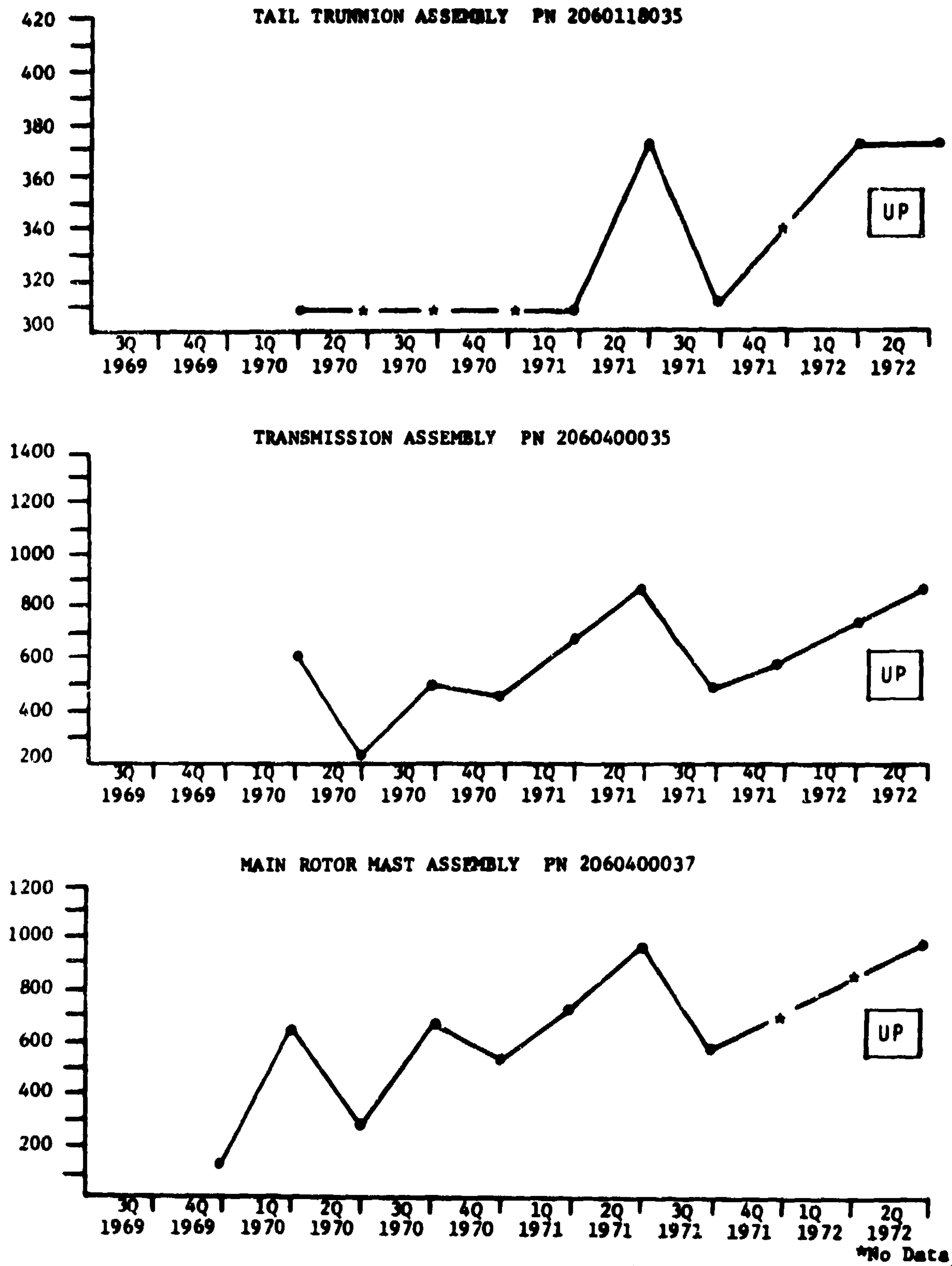

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Figure 6 (continued)

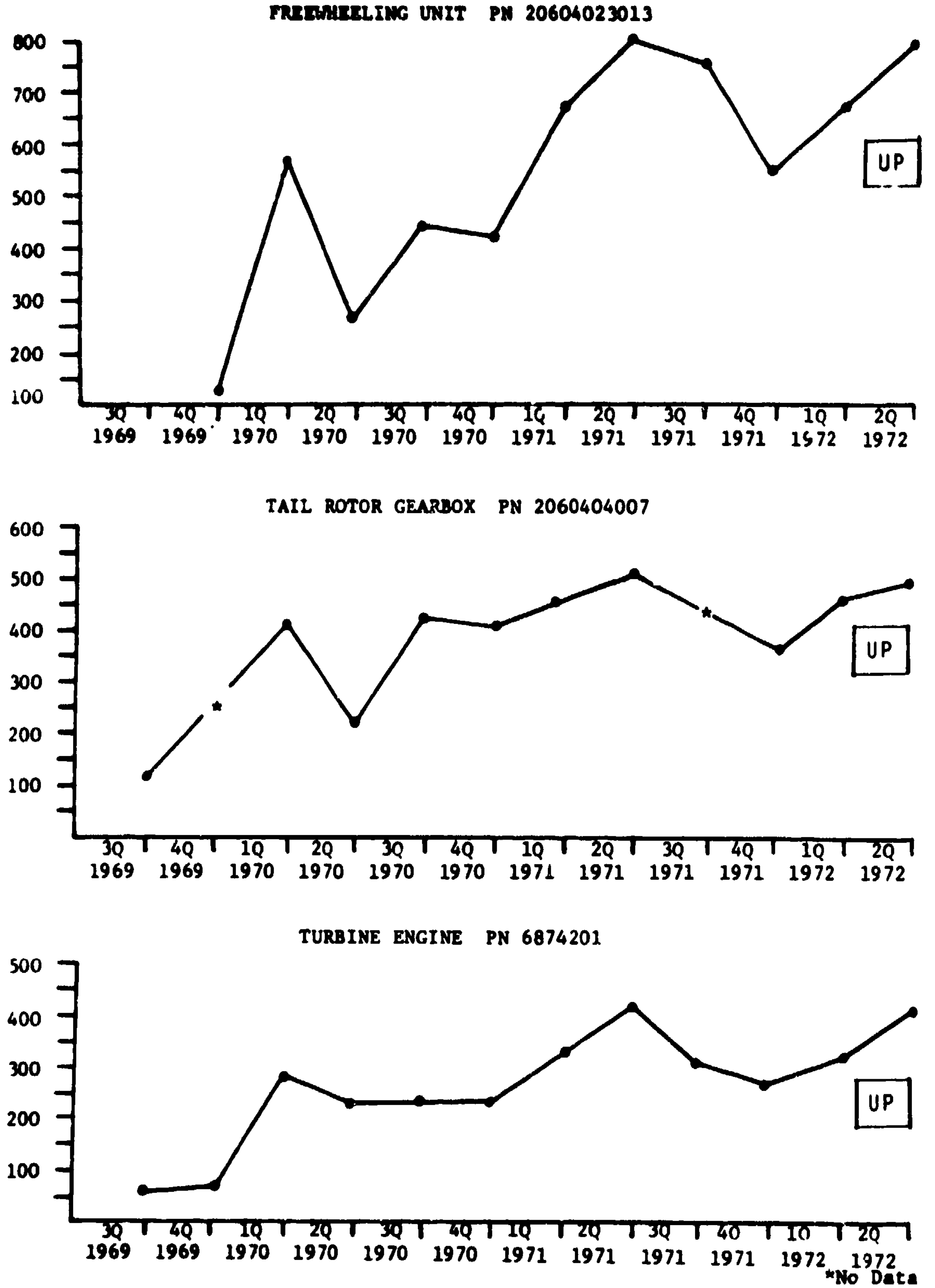

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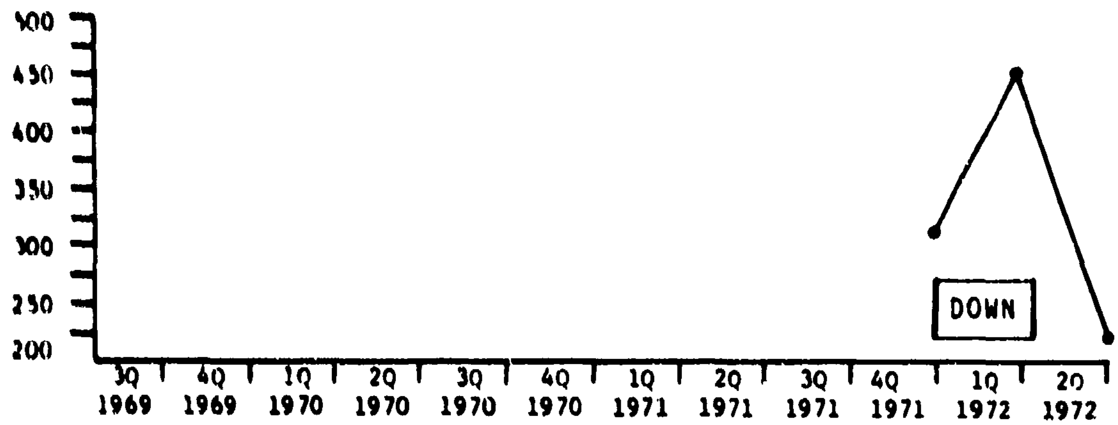
Figure 6 (continued)

FREEWHEELING UNIT PN 20604023019



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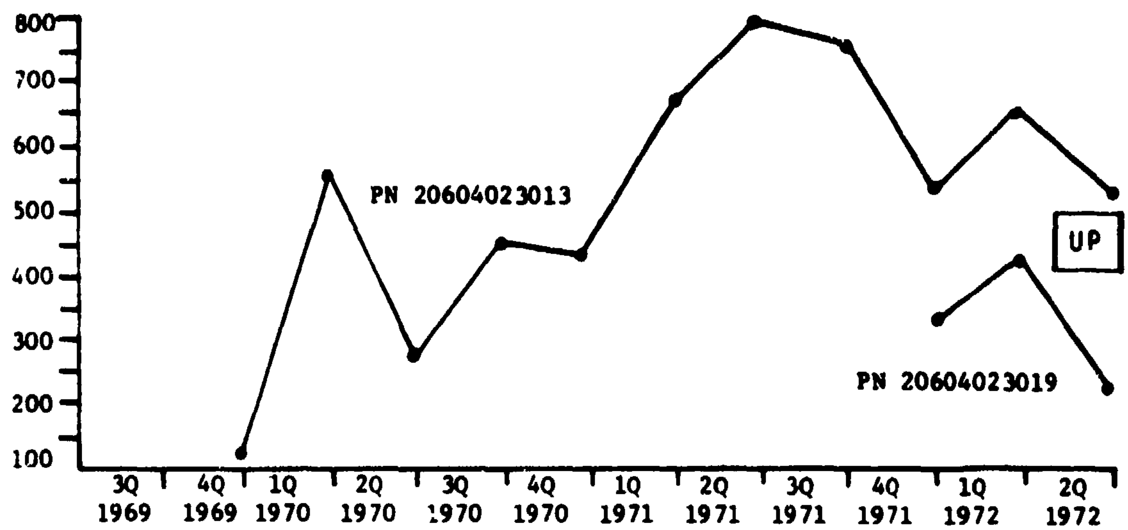
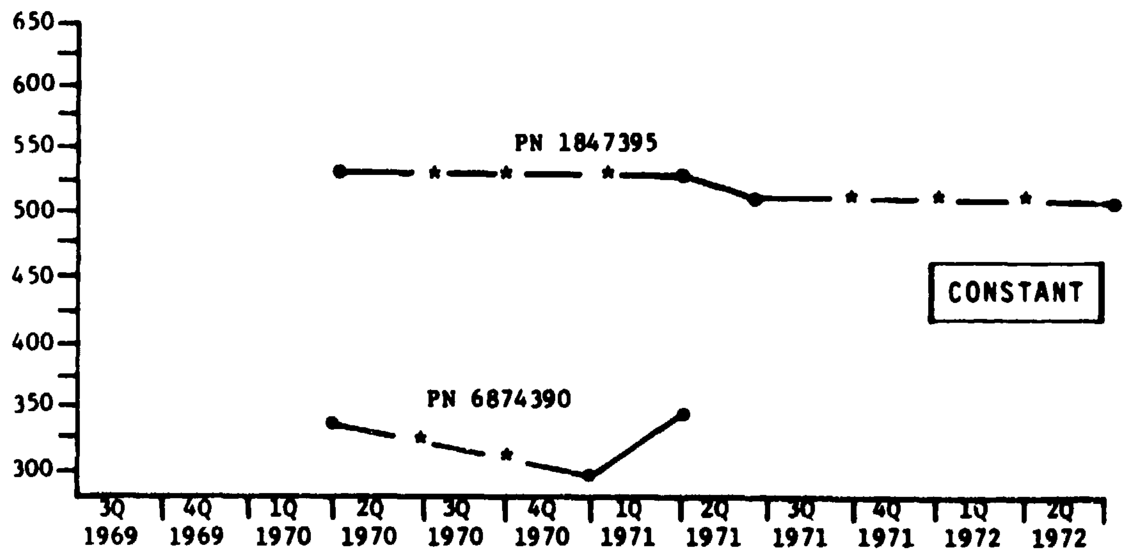
Source: Reference [2, pp. 418-25]--for all eight pages of this figure.

Figure 6 (continued)

FREEWHEELING UNIT



AXIAL COMPRESSOR



*No Data

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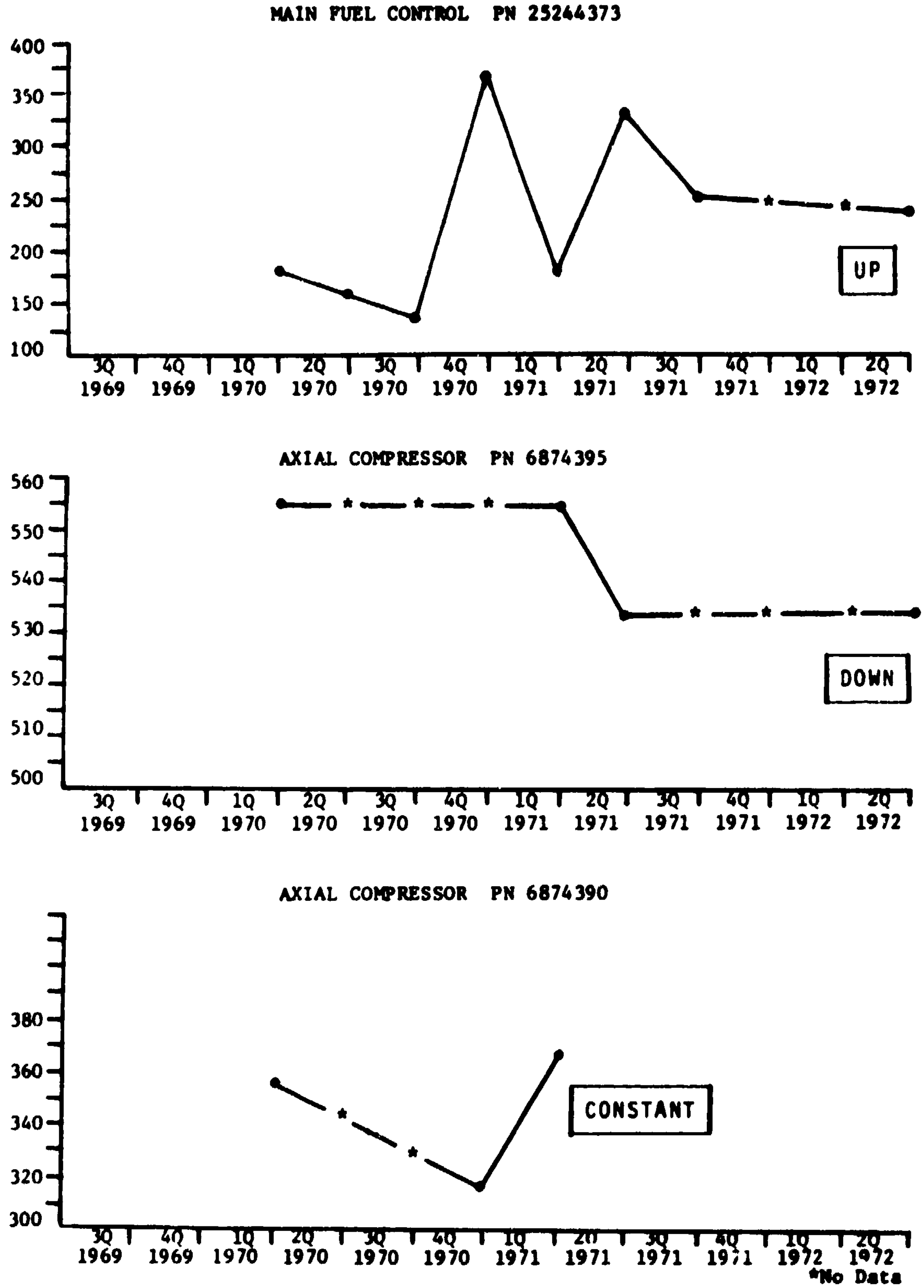
Figure 6 (continued)



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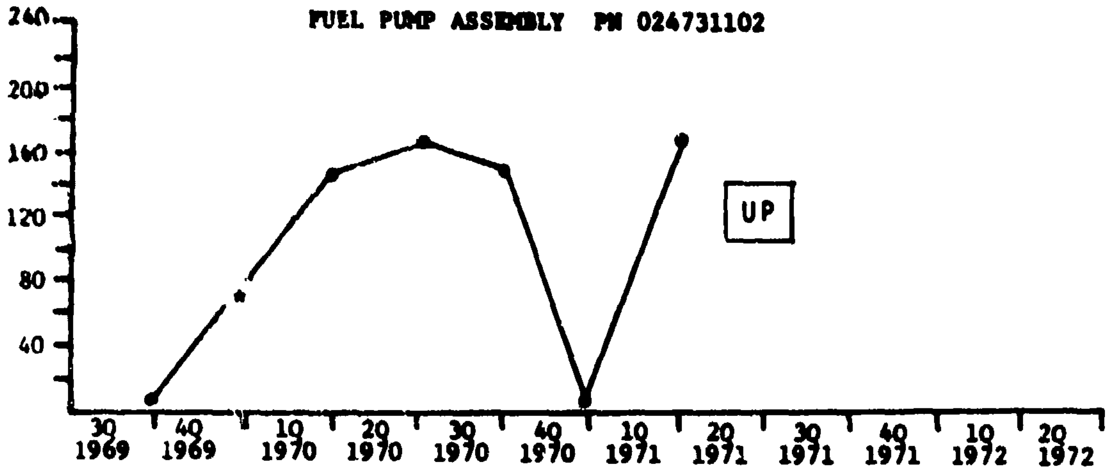

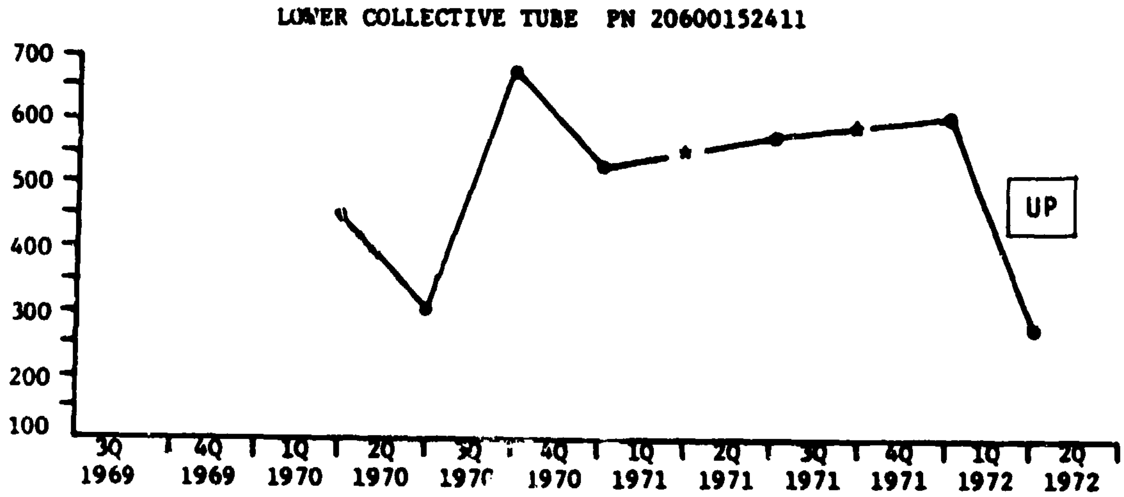

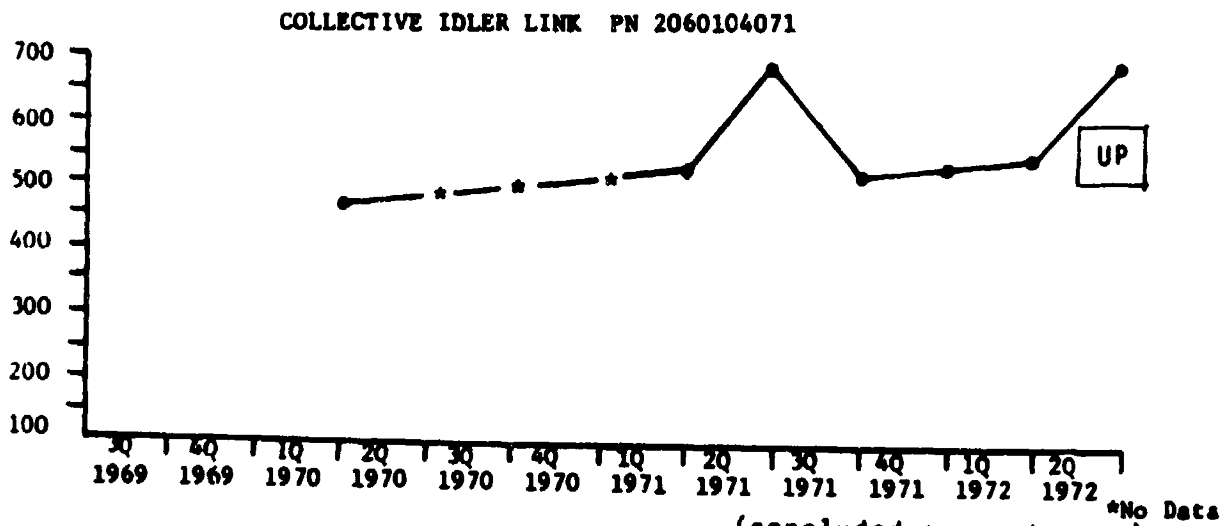

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Figure 6 (continued)

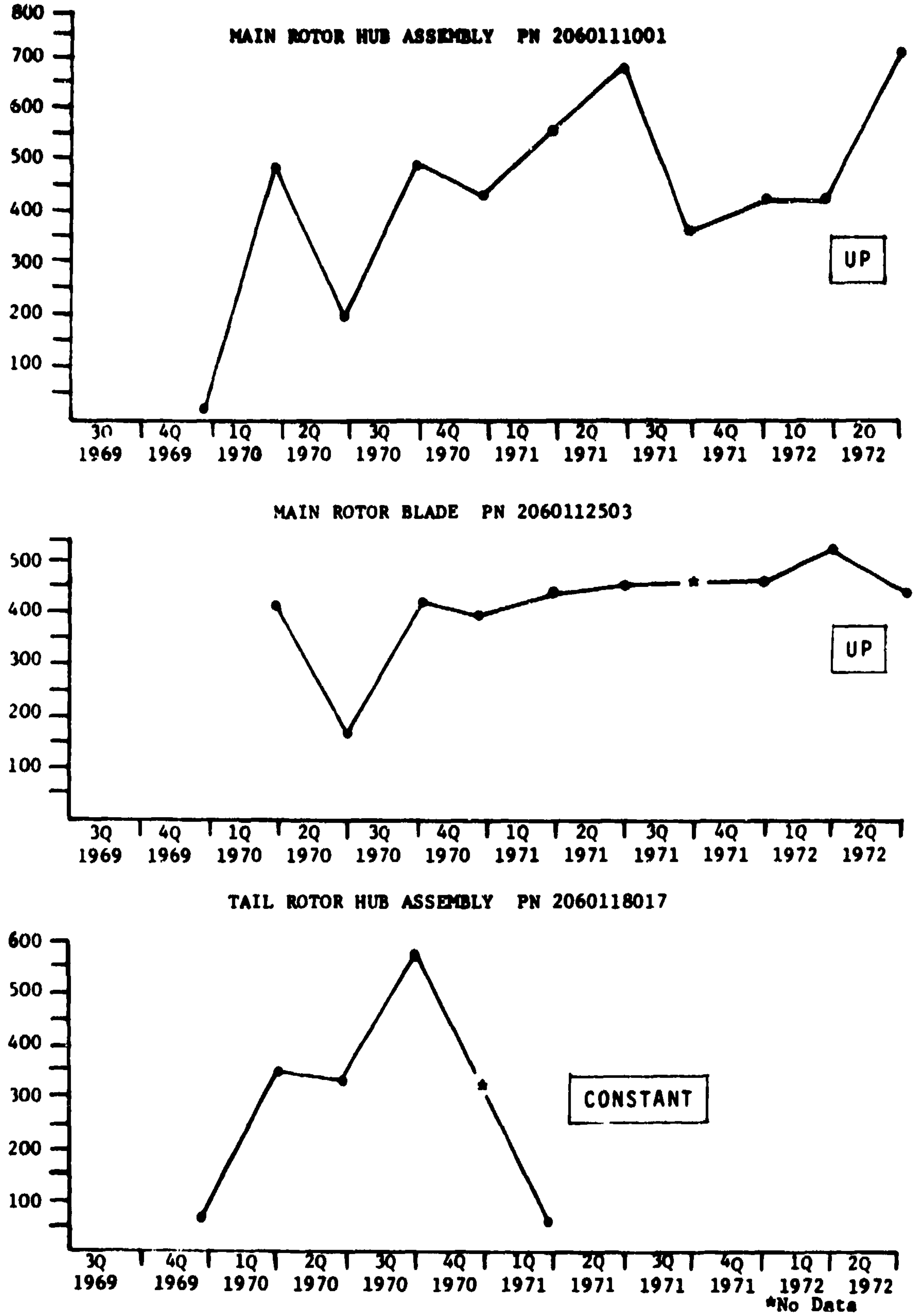


Figure 6 (concluded)

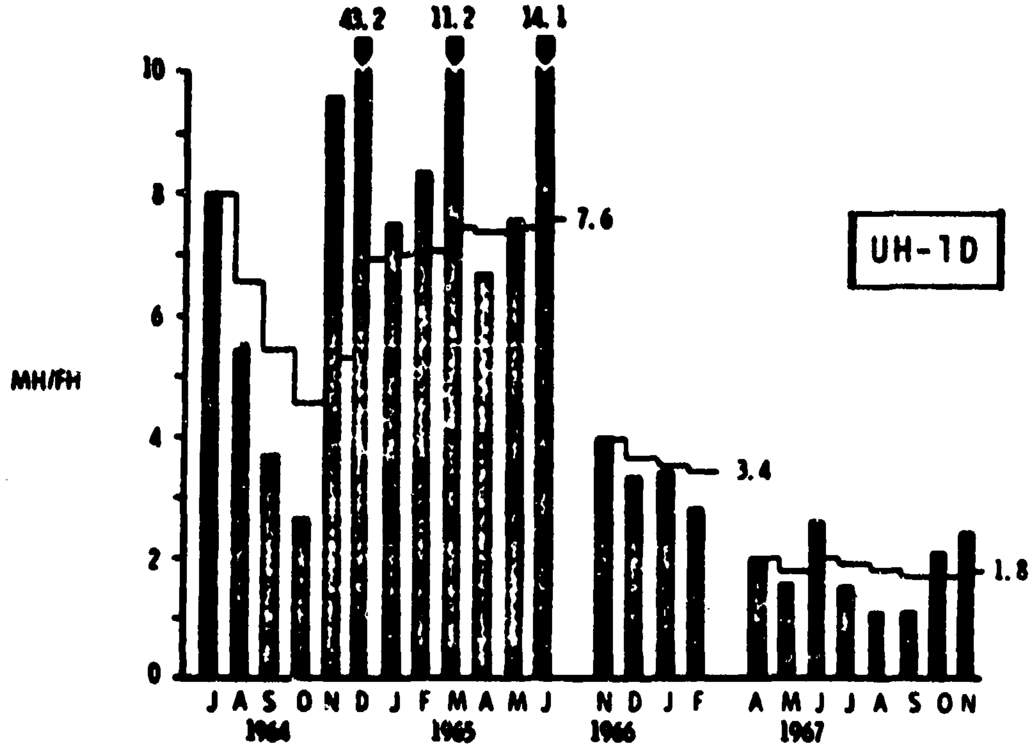
Suppose now that a component (X) on the OH-58A has a true MTTR of, say, 700 hours. When plotted versus calendar time (starting in the fourth calendar quarter of 1969), the MTTR for component X will thus show a steady increase--going from about 100 hours MTTR in CY 1969 to around 700 hours MTTR in the middle of CY 1972. To the eye, this increase looks like reliability improvement; but it is, in fact, nothing more than a transient that approaches a steady state. Hence, our conclusion is that it is very doubtful that the upward trends in Figure 6 are indicative of any reliability improvement. On the other hand, we can conclude that those components that showed level or downward trends in Figure 6 were definitely experiencing reliability degradation, since it is hard to envision how a steady-state MTTR could be reached by way of a decreasing transient.

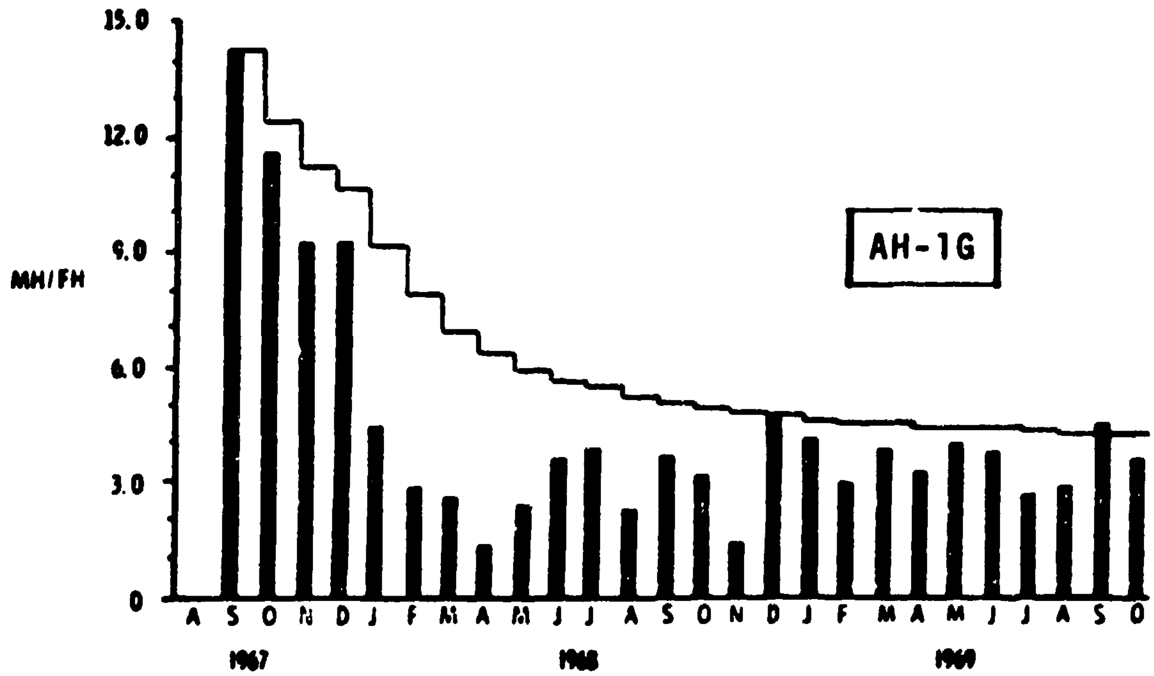
4. The AH-1G and the UH-1D

Figures 7 and 8 (taken from a paper by Bell Helicopter personnel) show trends in MMH/FH and operational availability for the UH-1D and AH-1G helicopters following their introductions into Army service. Since both helicopters were derivatives of earlier UH-1 models, the initial reliability growth period for each would not be representative of that for a completely new helicopter. Both the UH-1D and AH-1G seemed to experience reliability growth.

The MMH/FH for the UH-1D increased in 1965 relative to 1964, but the trend over the 1964-67 period was downward; the UH-1D operational availability increased somewhat over the same period.

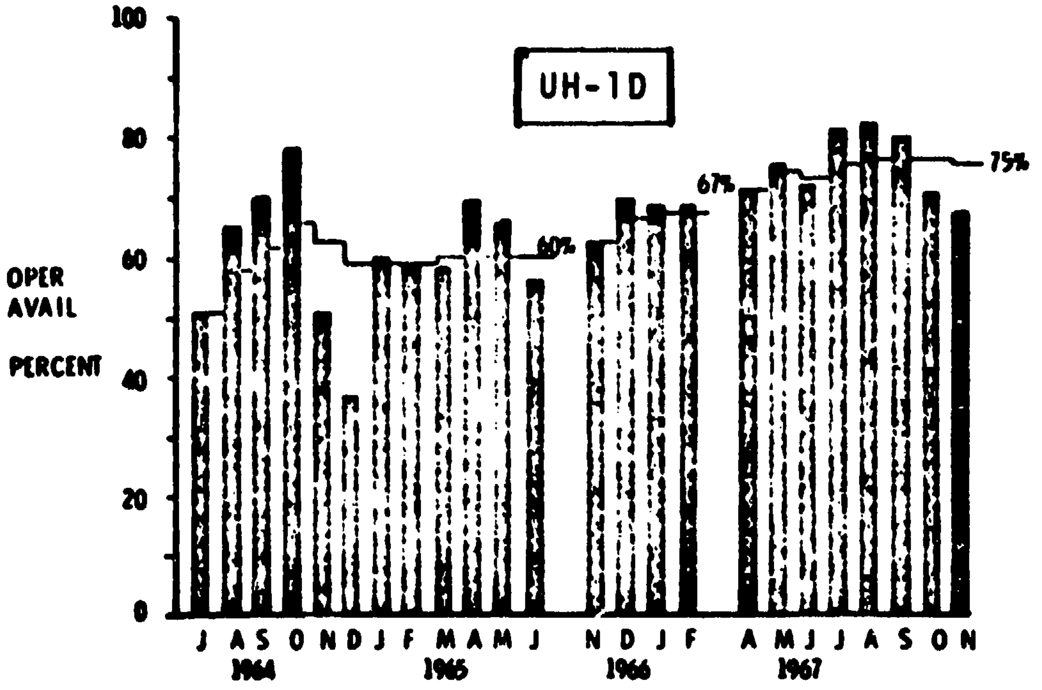
The MMH/FH for the AH-1G decreased over the period shown; however, all the decrease occurred in the first four months. Similarly, virtually all the improvement in the AH-1G availability took place in the first four or five months.

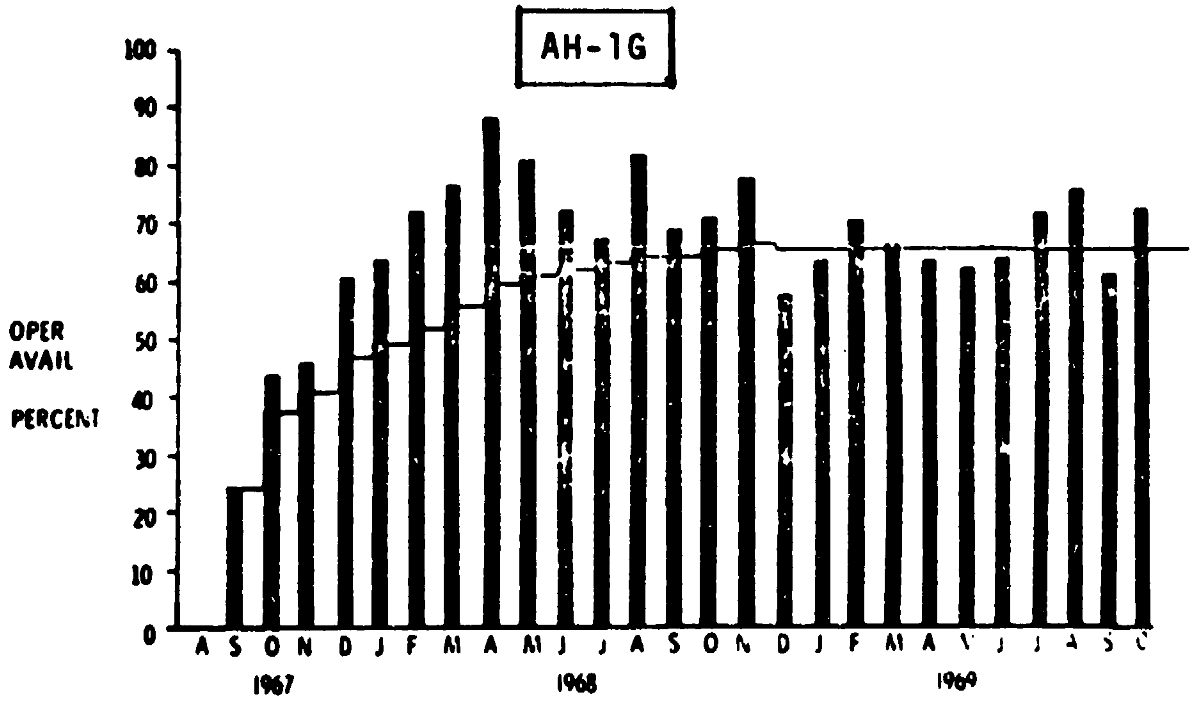




Source: Reference [6, p. 7].

Figure 7. MMH/FH FOR THE ARMY UH-1D AND AH-1G





Source: Reference [6, p. 8].

Figure 8. OPERATIONAL AVAILABILITY FOR THE ARMY UH-1D AND AH-1G

Figure 9 (from Bell Report 205-099-141) presents reliability data for the same UH-1D fleet as reported in Figures 7 and 8. The period covered is the first 13 months of Figure 7 and 8 (July 1964 through July 1965). The "operational reliability" of Figure 9 considered only primary failures that produced system or subsystem failures, while the "maintenance reliability" included all failures (primary, secondary, and externally caused) that necessitated unscheduled maintenance. The helicopter was broken down into 14 different systems, and similar plots were presented for each system. The operational reliability worsened over the 13 months for all systems except the power plant, and the maintenance reliability worsened for all systems except the oil-cooling, power-plant, and rotors systems. As would be expected, Figure 7 shows that MMH/FH increased over this same period, during which reliability worsened. Figure 7 indicates that MMH/FH declined in the following two years, but unfortunately we were not able to obtain reliability data for these following two years.

Figure 10 (from an AVSCOM report) shows the trends in MTTR for major items of the AH-1G for a later period of time than that covered by the Bell paper. There are 22 items covered in the various panels of Figure 10; by visual inspection, the trends were categorized as follows:

MTTR increased:	5
MTTR remained constant:	4
MTTR decreased:	13

The categorization is noted to the right of each trend by the words *up*, *constant*, or *down*. The relatively greater number of decreasing MTTRs would indicate that the helicopter as a whole experienced reliability degradation in MTTR over this period of time.

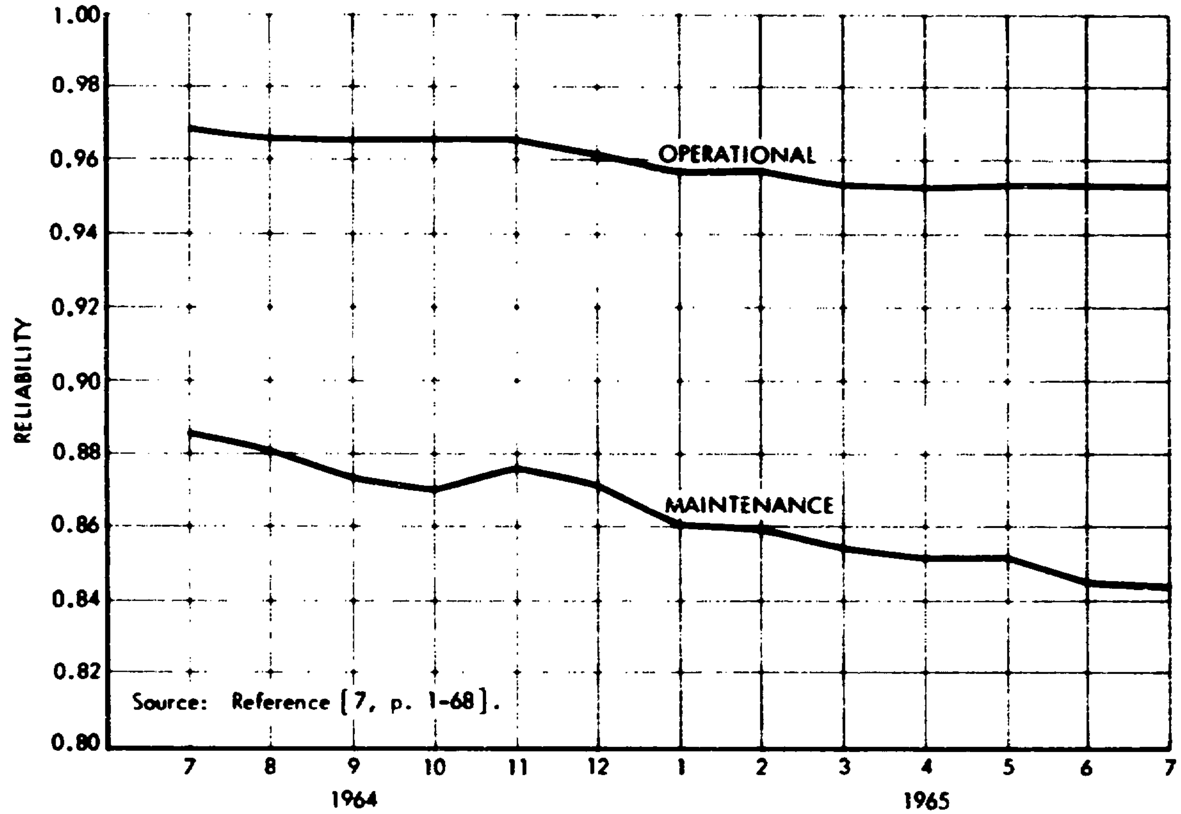


Figure 9. SYSTEM OPERATIONAL AND MAINTENANCE RELIABILITY OF THE HELICOPTER AS DETERMINED FROM FAILURE/DISCREPANCY REPORT DATA ON MONITORED UH-1D HELICOPTERS

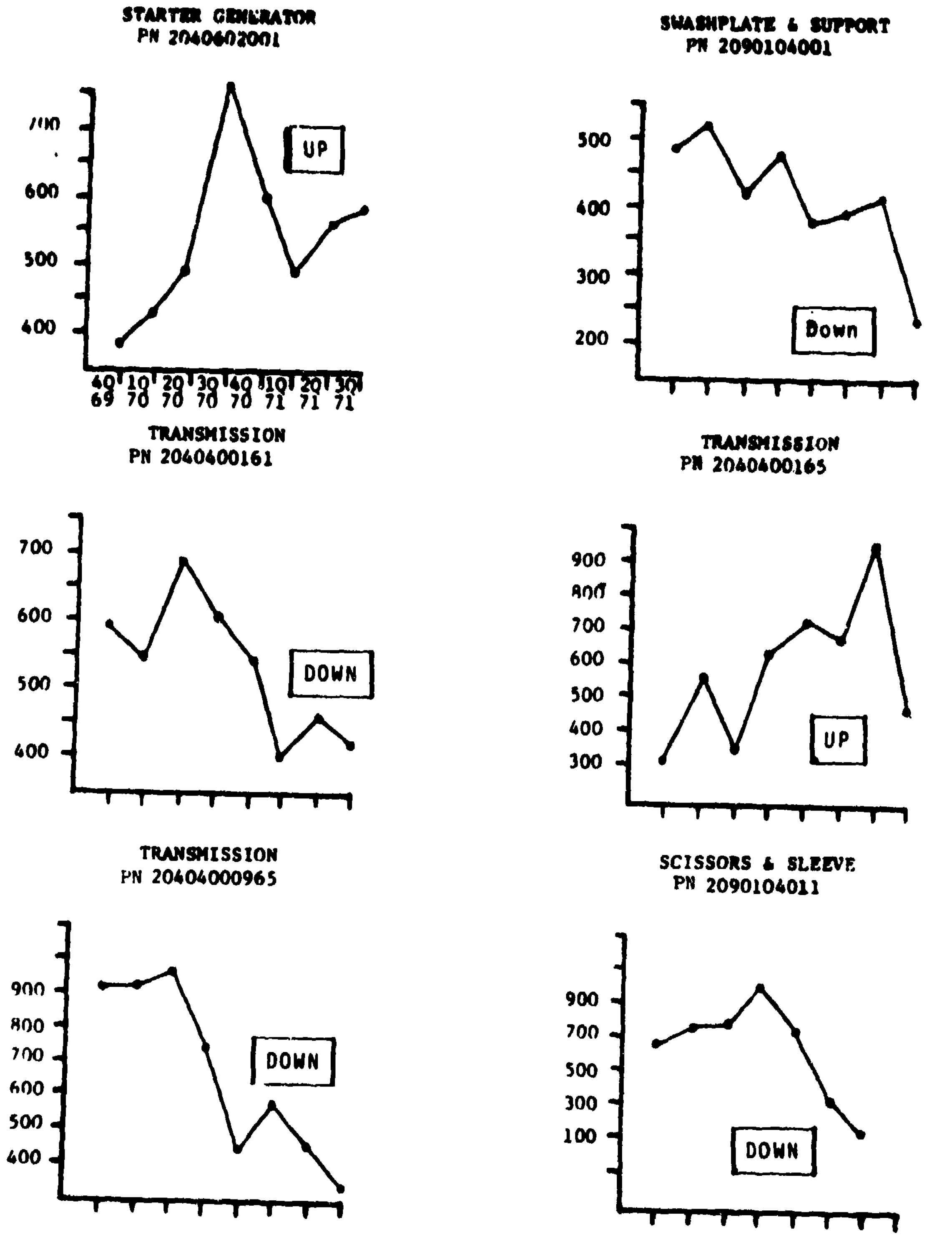


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Figure 10. MTTR FOR THE ARMY AH-1G, 1 OCTOBER 1969 - 30 SEPTEMBER 1971

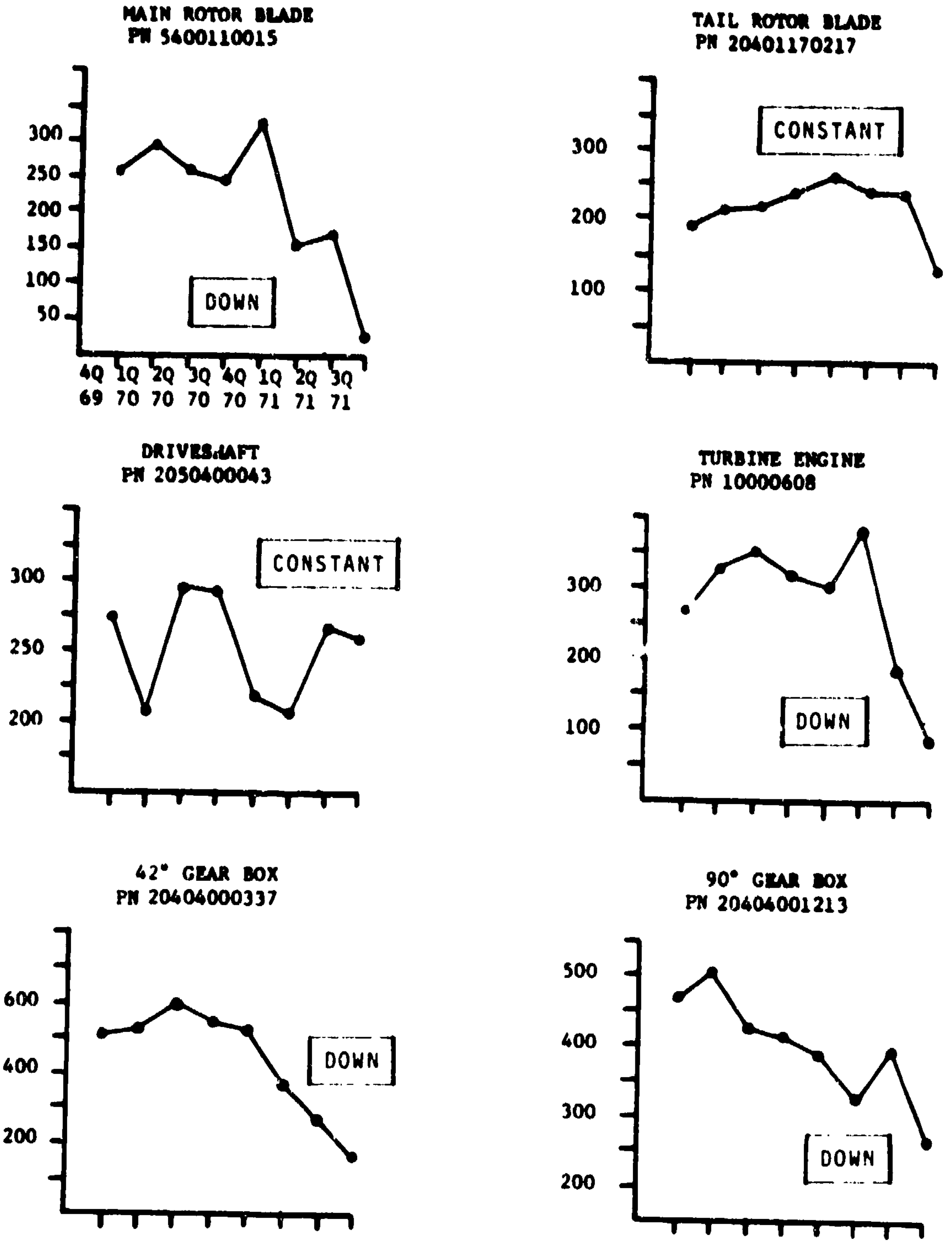

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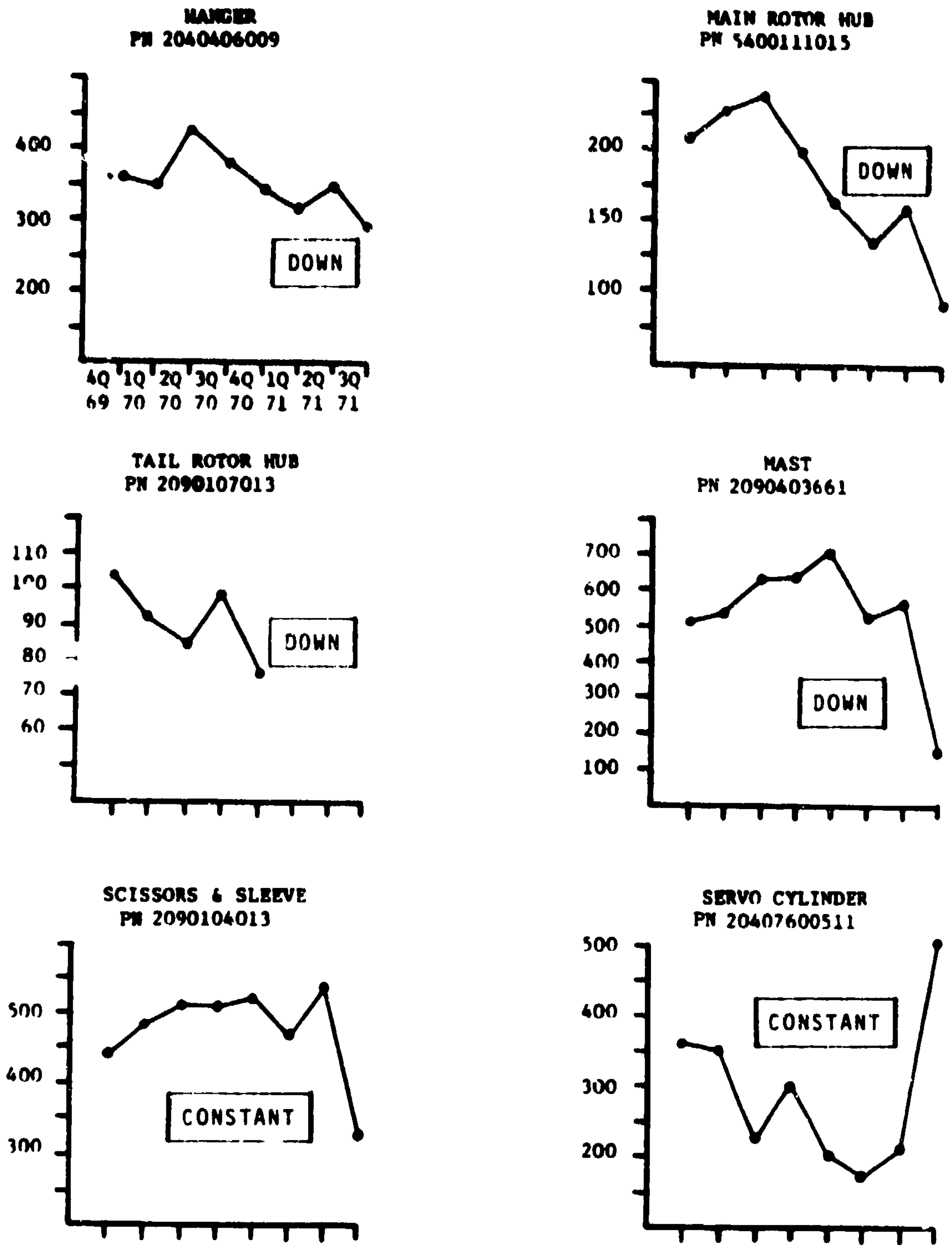
Figure 10 (continued)



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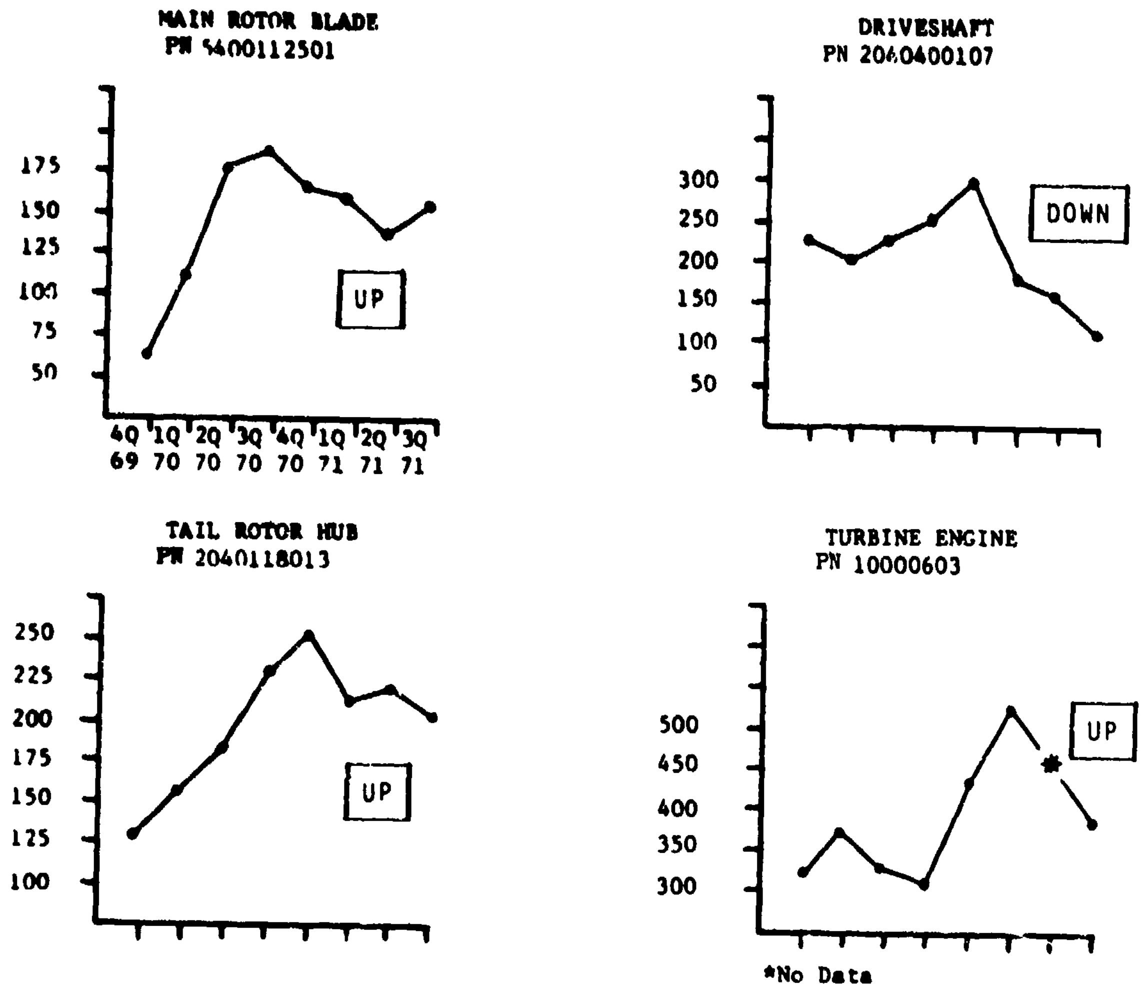

Source: Reference [3, pp. 202-05].

Figure 10 (concluded)

5. The CH-54A

Table 4 (reproduced directly from an AVSCOM report) presents mean time between flight aborts[1] for the CH-54A fleet. These data are plotted in Figure 11. As can be seen from the figure, the abort rate was quite variable over this period of time, but the overall trend was approximately constant.

Figure 12 (from the same AVSCOM report) shows the trends in mean time to removal for major items of the CH-54A. The various panels of Figure 12 cover 18 items; by visual inspection, the trends were categorized as follows:

MTTR increased:	10
MTTR remained constant:	5
MTTR decreased:	3

The categorization is noted to the right of each trend by the words *up*, *constant*, or *down*. The relatively greater number of increasing MTTRs seems to indicate that the helicopter as a whole experienced reliability growth in MTTR over this period of time. However, caution should be observed in drawing this conclusion, since there are many gaps in the data. It should also be noted that for certain items, the MTTR for some quarters may be based on only a single removal. Further, as discussed under the OH-58A trends (Subsection 3, above), some of the apparent improvement could be due to the accumulation of flight-hours on the components over time.

6. Maintenance Man-Hours per Flight-Hour (MMH/FH)

The Army publishes manuals giving manpower requirements for various types of equipment. Since these documents are reissued periodically, they should show trends in helicopter maintenance man-hours over calendar time.

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[1]The term "flight abort" means the premature termination of a mission for any reason.

Table 4. ABORT DATA FOR THE ARMY CH-54A, 1 JANUARY 1969 - 31 MARCH 1973

Quarters	Average Inventory	Flight Hours	Number of Aborts	MTB Aborts
1st Qtr. 69	55	5063	10	506.3
2nd Qtr. 69	56	1702	4	425.5
3rd Qtr. 69	58	5417	9	601.9
4th Qtr. 69	58	5167	4	1291.8
1st Qtr. 70	58	5173	13	397.9
2nd Qtr. 70	58	6091	8	761.4
3rd Qtr. 70	57	4025	8	503.1
4th Qtr. 70	56	2904	3	968.0
1st Qtr. 71	54	2816	11	256.0
2nd Qtr. 71	52	2405	3	801.7
3rd Qtr. 71	51	2390	6	398.3
4th Qtr. 71	50	1501	4	375.3
1st Qtr. 72	50	1189	0	1189.0
2nd Qtr. 72	49	1524	4	381.0
3rd Qtr. 72	49	1418	1	1418.0
4th Qtr. 72	48	974	3	324.7
1st Qtr. 73	47	874	3	291.3

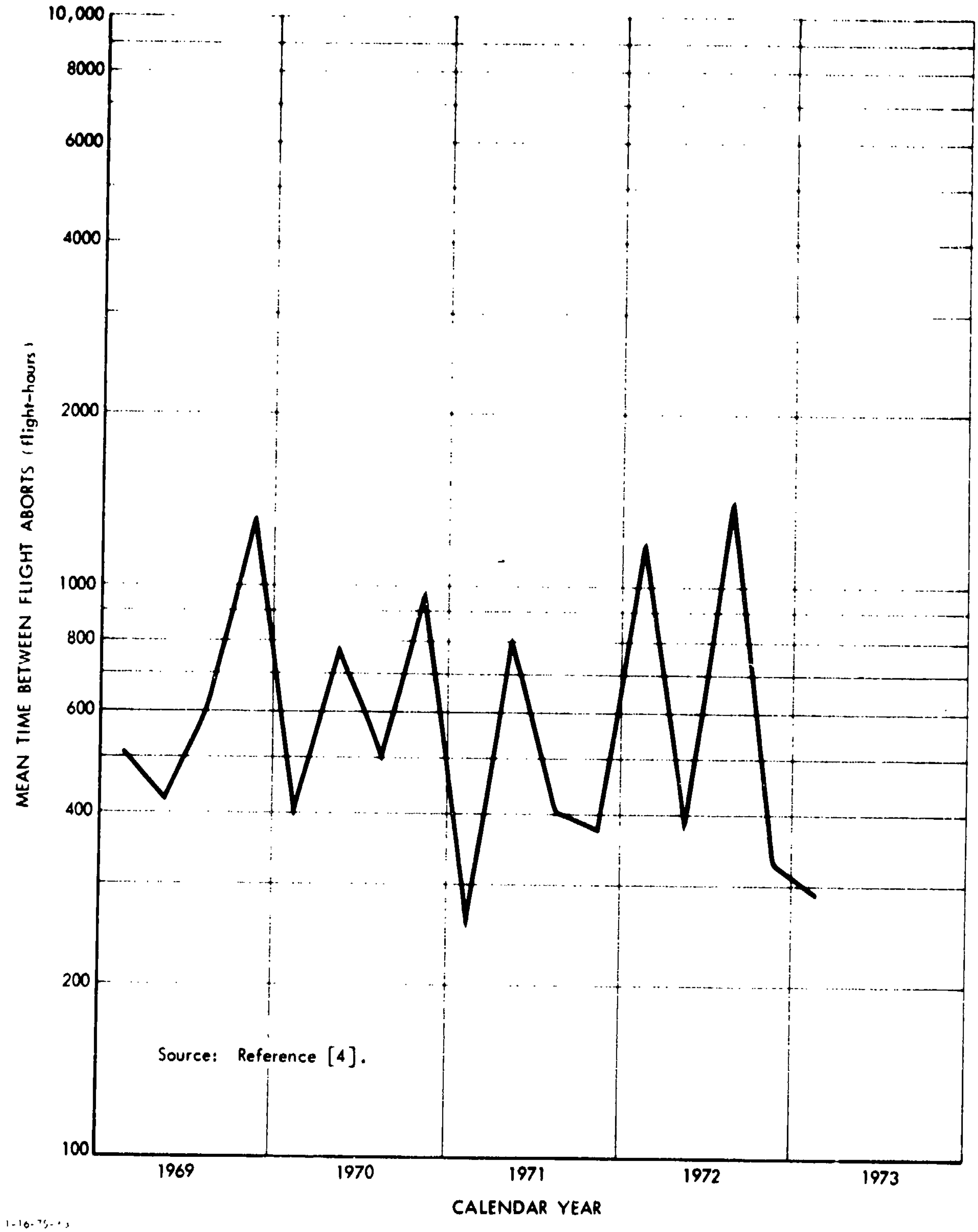
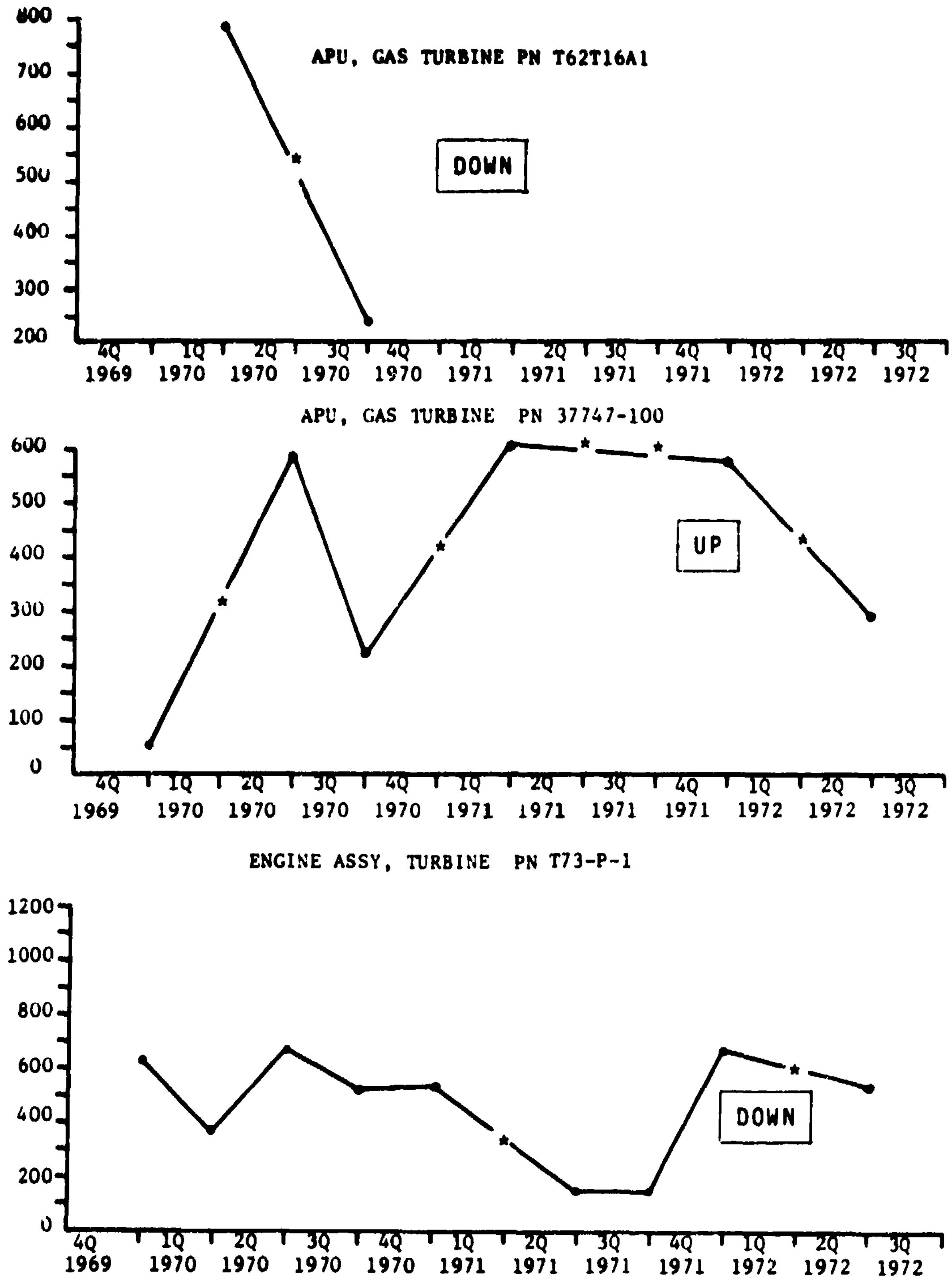


Figure 11. MEAN TIME BETWEEN FLIGHT ABORTS FOR THE ARMY CH-54A



* Indicates no data available for this quarter

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Figure 12. MTTR TRENDS FOR THE ARMY CH-54A, 1 OCTOBER 1969 - 30 SEPTEMBER 1972

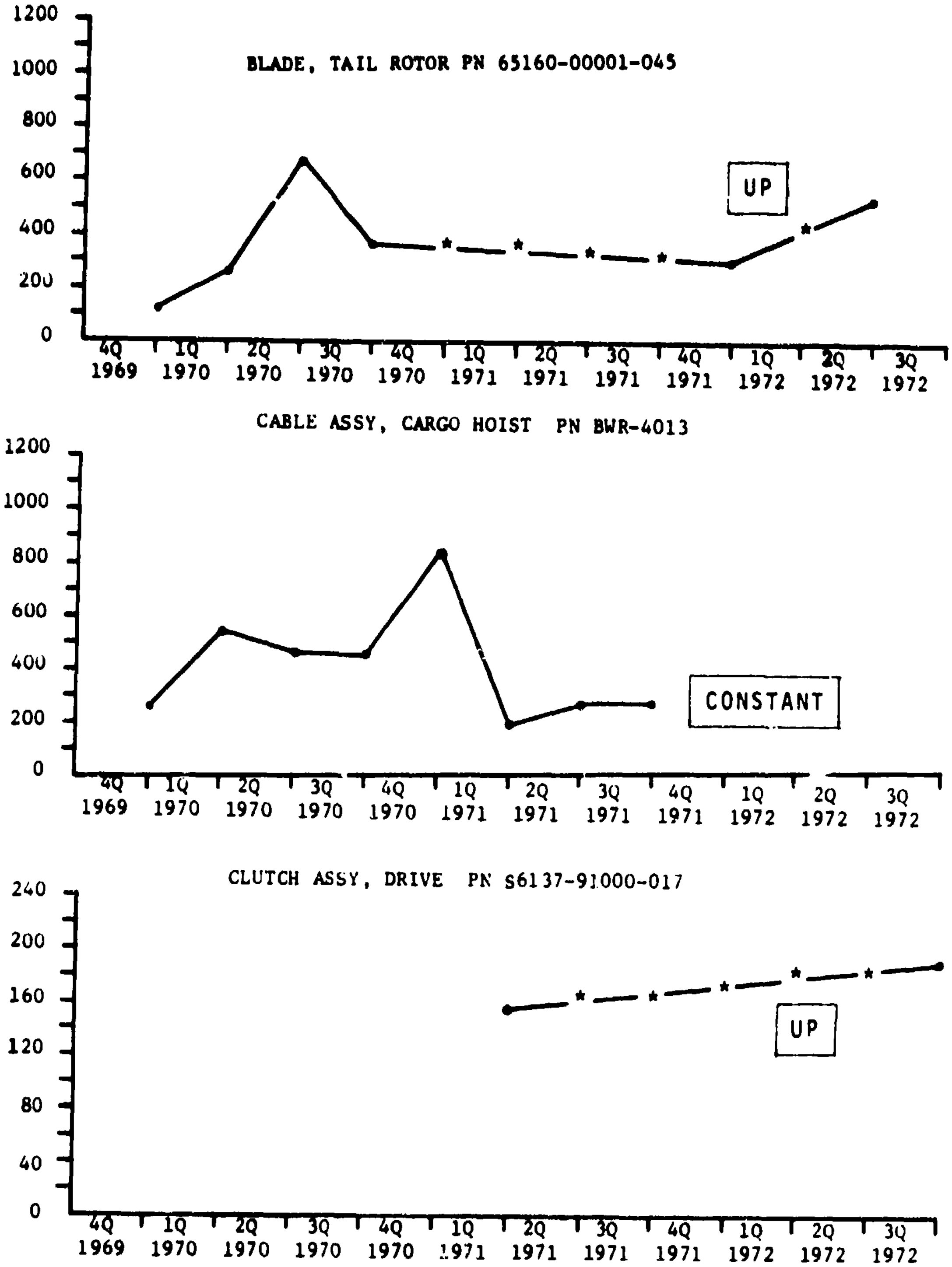

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Figure 12 (continued)

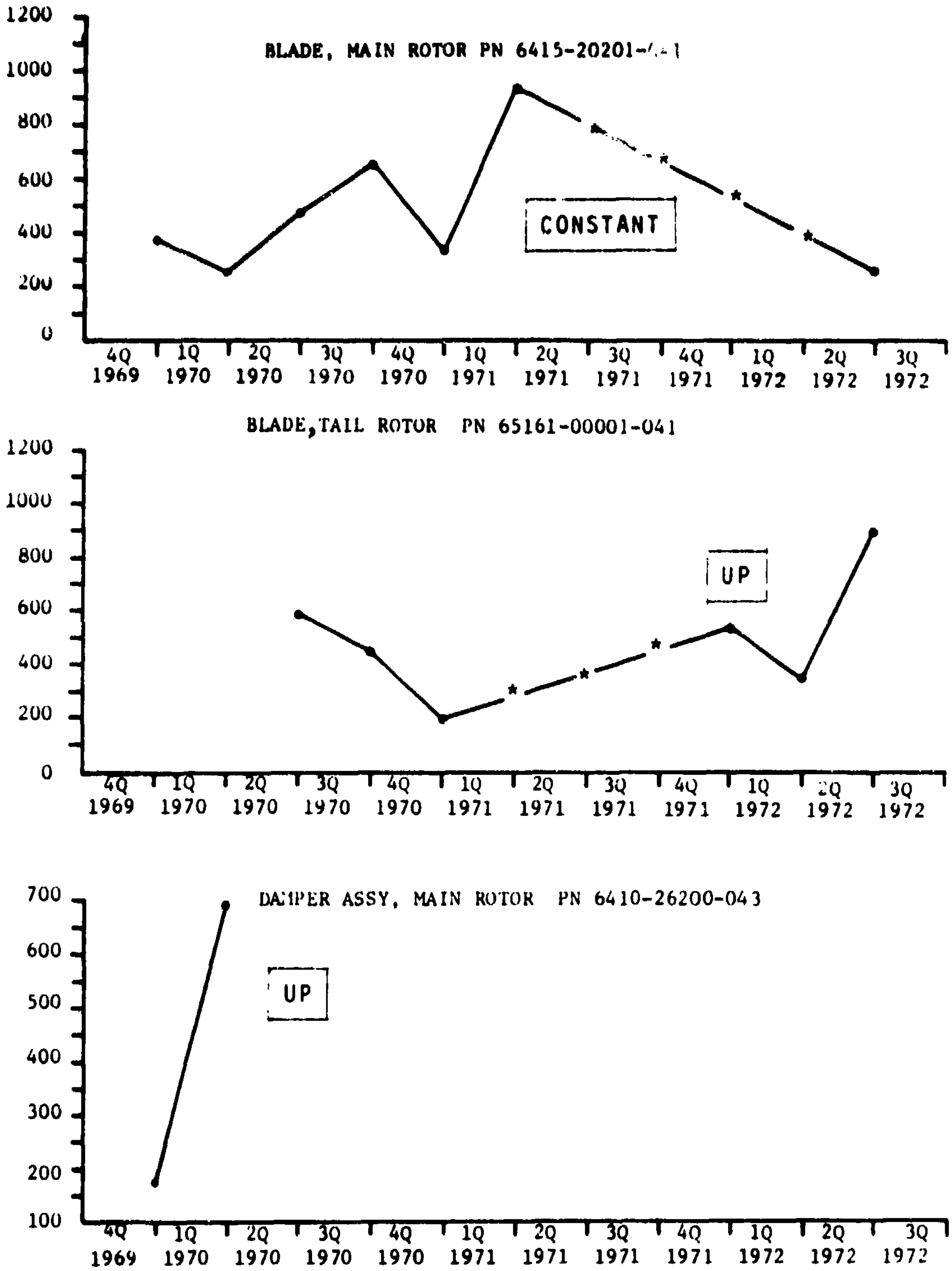

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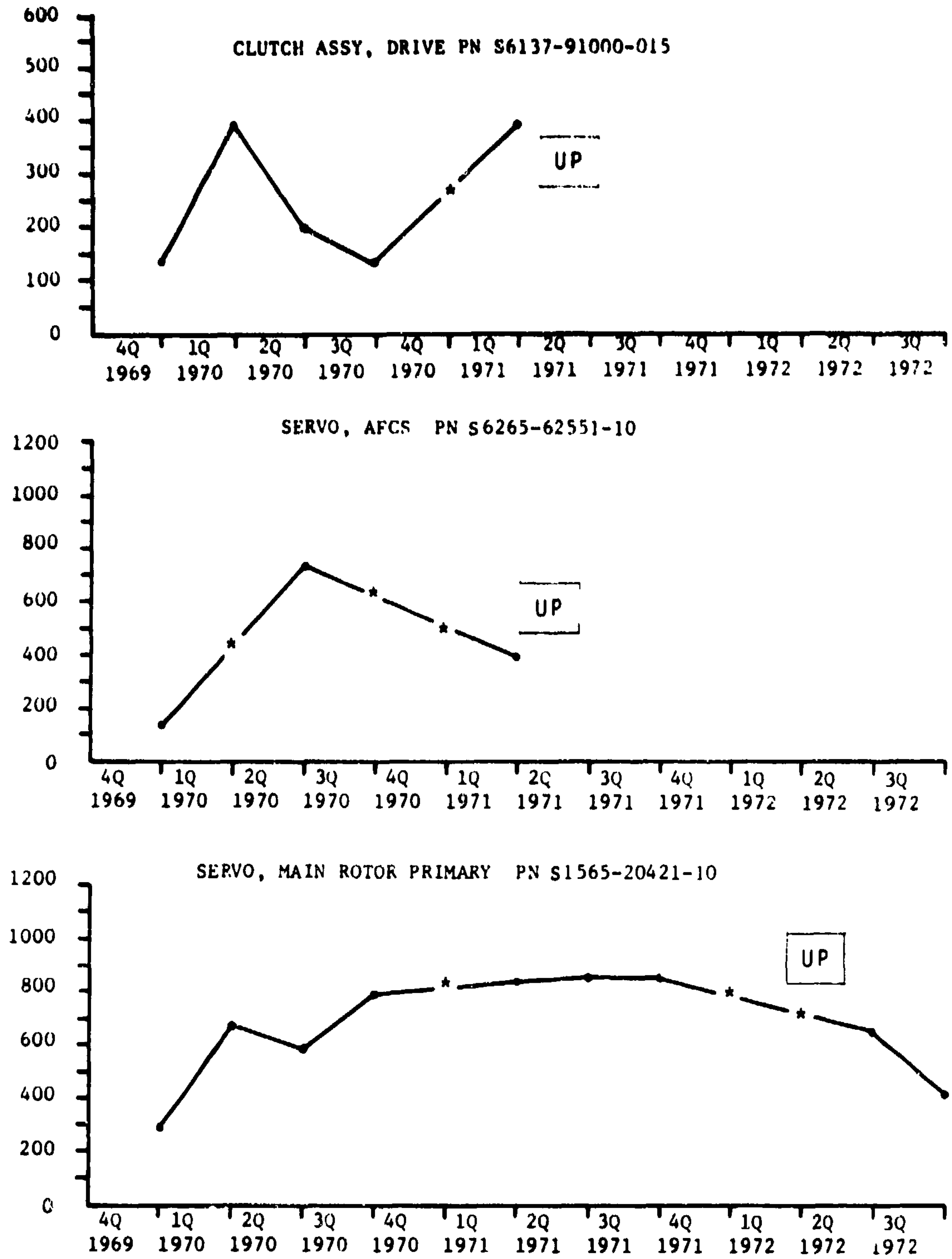
Figure 12 (continued)



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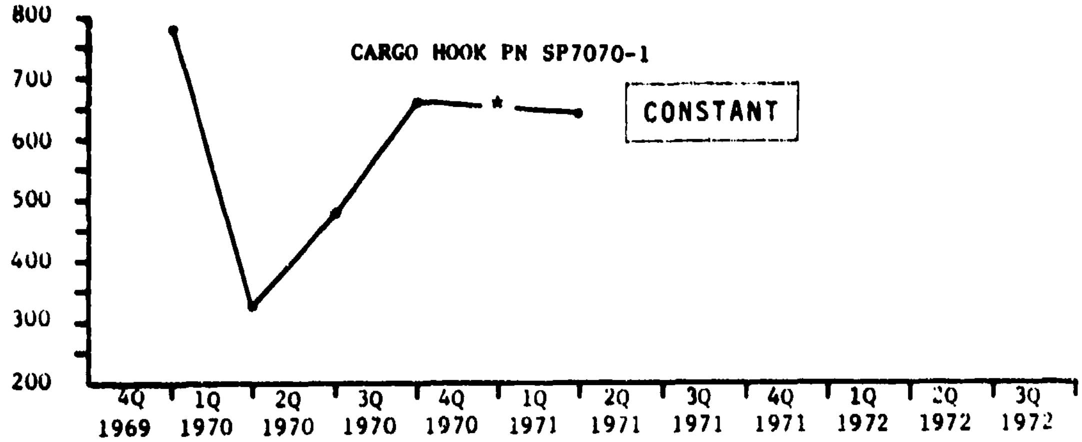

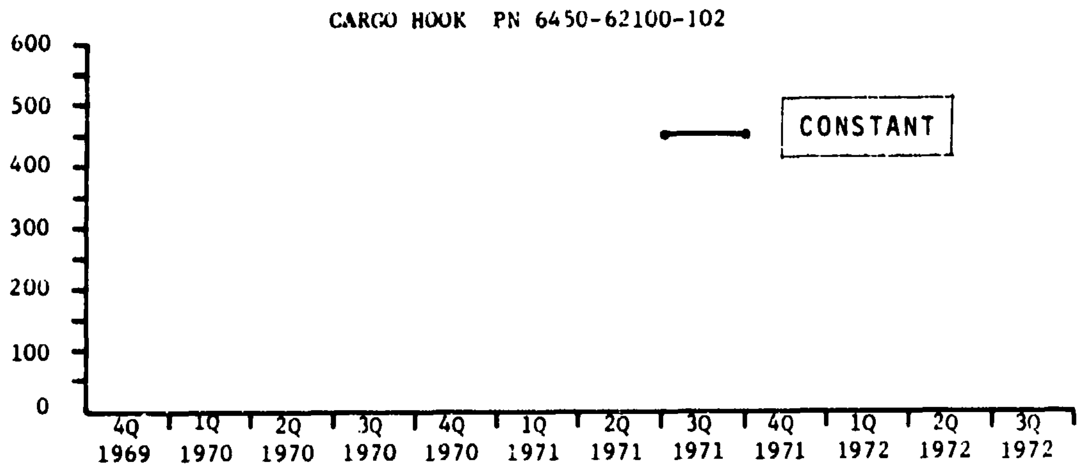

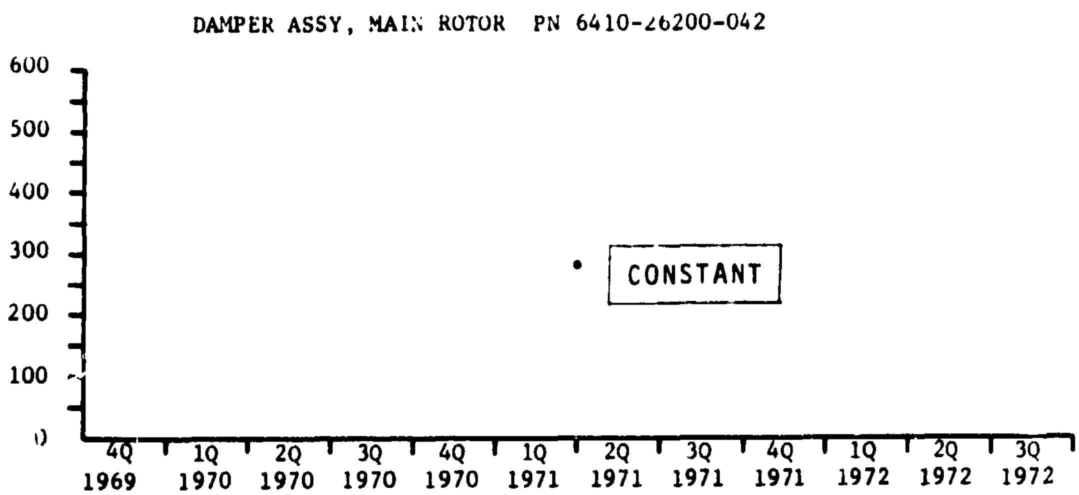

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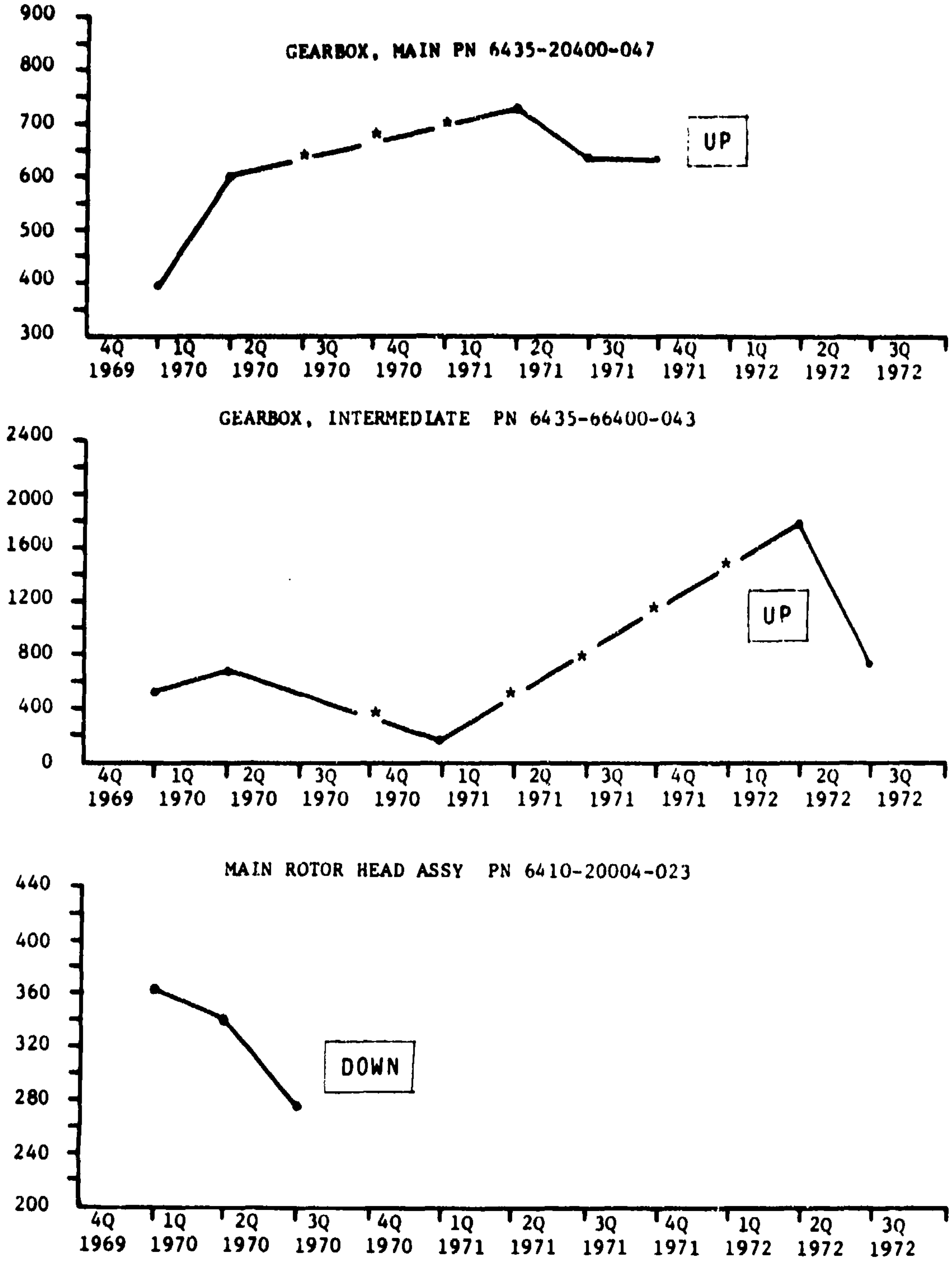
Figure 12 (continued)



* Indicates no data available for this quarter

Figure 12 (concluded)

Table 5 presents all the helicopter maintenance man-hour data published by the Army in general service manuals since April 1958. As can be seen in the sources given at the bottom of Table 5, the Army data have been published in a number of different regulations and manuals. In all, eight documents have been published since April 1958--seven of them since February 1968. Data are reported for three levels of maintenance: organizational, direct support, and general support. However, as can be seen by the dashes in the table, not all three levels are reported in every document. The April 1958 document reported only organizational data; the next three documents reported only direct-support and general-support data, while the last four documents reported data for all three levels of maintenance.

In some cases, the designation of the helicopter type varied among documents. For example, the May 1971 document showed only a single entry for all CH-47 aircraft, while the September 1971 document showed figures for the CH-47A, CH-47B, and CH-47C.

In all cases, the figures include a "1.4 indirect productive time factor," and include both on- and off-aircraft maintenance. The figures of Table 5 are taken directly from the Army publications in all but two cases: the organizational maintenance in the May 1971 and March 1973 documents showed "direct man-hours per flight hour." These figures were multiplied by 1.4 to make them consistent with all the other figures.

Presumably, the maintenance man-hours, which are provided by AVSCOM(AMSAV-FP), should reflect actual Army experience. Unfortunately, an examination of the figures indicates that such may not be the case. For example, note the direct-support figures for the H-13 in the last four publications (1.40, 2.20, 1.40, 2.20). These figures look suspiciously as though they were generated by clerks copying figures from previous documents and making mistakes in the process. With this caveat, let us examine the data relative to trends over time.

Table 5. ARMY MMH/FH

Helicopter Type	Apr 1968	Feb 1968	May 1968	July 1969	May 1971	Sep 1971	Mar 1973	May 1973
Organizational Maintenance								
H-13	4.00	--	--	--	2.65	2.65	2.65	2.65
H-23	4.00	--	--	--	2.65	2.07	2.65	--
H-19	7.00	--	--	--	--	--	--	--
H-21	10.80	--	--	--	--	--	--	--
H-34	10.80	--	--	--	7.98	8.60	7.98	--
H-37	15.60	--	--	--	--	--	--	--
UH-1A/B/C	6.00	--	--	--	3.35	3.35	3.35	3.35
UH-1D/H	--	--	--	--	3.25	3.25	3.25	3.25
AH-1G	--	--	--	--	4.05	4.05	4.05	4.05
OH-6/OH-58	--	--	--	--	2.25	2.25	2.25	2.25
CH-47	--	--	--	--	12.70	--	12.70	--
CH-47A	--	--	--	--	--	12.73	--	12.73
CH-47B	--	--	--	--	--	12.32	--	12.32
CH-47C	--	--	--	--	--	11.30	--	11.30
CH-54	--	--	--	--	17.81	17.81	17.81	17.81
Direct Support								
H-13	--	1.40	1.40	1.40	1.40	2.20	1.40	2.20
H-23	--	1.54	1.54	1.54	1.54	2.52	1.54	--
H-19	--	4.62	4.62	4.62	--	--	--	--
H-21	--	5.46	5.46	5.46	--	--	--	--
H-34	--	4.76	4.76	4.76	4.76	9.72	4.76	--
H-37	--	7.56	7.56	7.56	--	--	--	--
UH-1	--	2.10	2.10	2.10	--	--	--	--
UH-1B/C	--	--	--	--	2.79	2.79	2.79	2.79
UH-1D/H	--	--	--	--	2.41	2.41	2.41	2.41
AH-1G	--	2.10	2.10	2.10	2.62	2.62	2.62	2.62
OH-6	--	1.19	1.19	1.19	2.81	2.81	2.81	2.81
OH-58	--	--	--	--	2.81	2.81	2.81	2.81

(continued on next page)

Table 5 (continued)

Helicopter Type	Apr 1958	Feb 1968	May 1968	July 1969	May 1971	Sep 1971	Mar 1973	May 1973
Direct Support								
CH-47	--	8.12	8.12	8.12	10.73	--	10.73	--
CH-47A	--	--	--	--	--	10.74	--	10.74
CH-47B	--	--	--	--	--	8.36	--	8.36
CH-47C	--	--	--	--	--	12.31	--	12.31
CH-54	--	13.60	13.60	13.60	7.85	7.85	7.85	7.85
General Support								
H-13	--	1.12	1.12	1.12	1.12	1.78	1.12	1.78
H-23	--	1.12	1.12	1.12	1.12	3.09	1.12	--
H-19	--	2.52	2.52	2.52	--	--	--	--
H-21	--	2.80	2.80	2.80	--	--	--	--
H-34	--	3.22	3.22	3.22	3.22	6.58	3.22	--
H-37	--	5.04	5.04	5.04	--	--	--	--
UH-1	--	1.54	1.54	1.54	--	--	--	--
UH-1B/C	--	--	--	--	2.30	2.30	2.30	2.30
UH-1D/H	--	--	--	--	2.02	2.02	2.02	2.02
AH-1G	--	1.54	1.54	1.54	2.18	2.18	2.18	2.18
OH-6	--	1.04	1.04	1.04	0.67	0.67	0.67	0.67
OH-58	--	--	--	--	0.67	0.67	0.67	0.67
CH-47	--	5.18	5.18	5.18	7.85	--	7.85	--
CH-47A	--	--	--	--	--	7.85	--	7.85
CH-47B	--	--	--	--	--	6.43	--	6.43
CH-47C	--	--	--	--	--	8.85	--	8.85
CH-54	--	2.98	2.98	2.98	5.66	5.66	5.66	5.66

Sources: References [8], [9], [10], and [11].

In the case of organizational maintenance, no data were published between April 1958 and May 1971. For the four aircraft reported in both time periods, all showed significant reductions in MMH/FH. It is possible that some definitional change caused this reduction. From May 1971 to May 1973, the MMH/FH were essentially constant for all types.

In the case of direct support, the September 1971 figures for the H-13, H-23, and H-34 appear questionable; they are much higher than those of both the immediately preceding and the immediately following periods. They should probably be ignored. The UH-1, AH-1G, OH-6, and CH-47 are higher in the last four periods than in the first three. The reverse is true for the CH-54. Hence, the direct-support MMH/FH appeared to worsen for four types, improve for one type, and remain constant for the other seven types.

In the case of general support, the September 1971 figures for the H-13, H-23, and H-34 again appear questionable; they are much higher than those of both the immediately preceding and the immediately following periods. The UH-1, AH-1G, CH-47, and CH-54 are higher in the last four periods than in the first three. The reverse is true for the OH-6. Hence, the general support MMH/FH appeared to worsen for four types, improve for one type, and remain constant for the other seven types.

The results of this analysis are summarized in Table 6. Even including the April 1958 data, there are more cases in which MMH/FH worsened than in which they improved. To the extent that these data can be believed, they show, in general, that MMH/FH remain constant over time; if they do change, they tend to worsen more often than they improve.

Table 6. SUMMARY OF CHANGES IN ARMY MMH/FH

MMH/FH Change	Number of Helicopter Types	
	Including April 1958 Data	Excluding April 1958 Data
Worsened	8	8
Improved	6	2
Constant	20	20

Table 7 presents some additional MMH/FH data published recently by AVSCOM.

Table 7. ARMY ON-AIRCRAFT MMH/FH

Aircraft	Data Time Frame	MMH/FH
OH-58A	Jan 70-Jun 71	2.06
AH-1G	Jul 70-Jun 71	5.53
CH-54A	Jul 70-Dec 72	14.50
CH-47A	Apr 71-Mar 73	14.94

The figures of Table 7 represent on-aircraft maintenance only and are therefore lower than those of Table 5, which include both on- and off-aircraft maintenance. The total MMH/FH for all levels of maintenance for all the turbine-powered helicopters of Tables 5 and 7 are plotted in Figure 13. The data points from Table 5 lie in a nearly straight line on the semi-log plot. The data points from Table 7 do not lie in a straight line; a trend line parallel to that of the upper trend has been fitted through them. There is a fairly wide range of uncertainty at the lower end of this trend.

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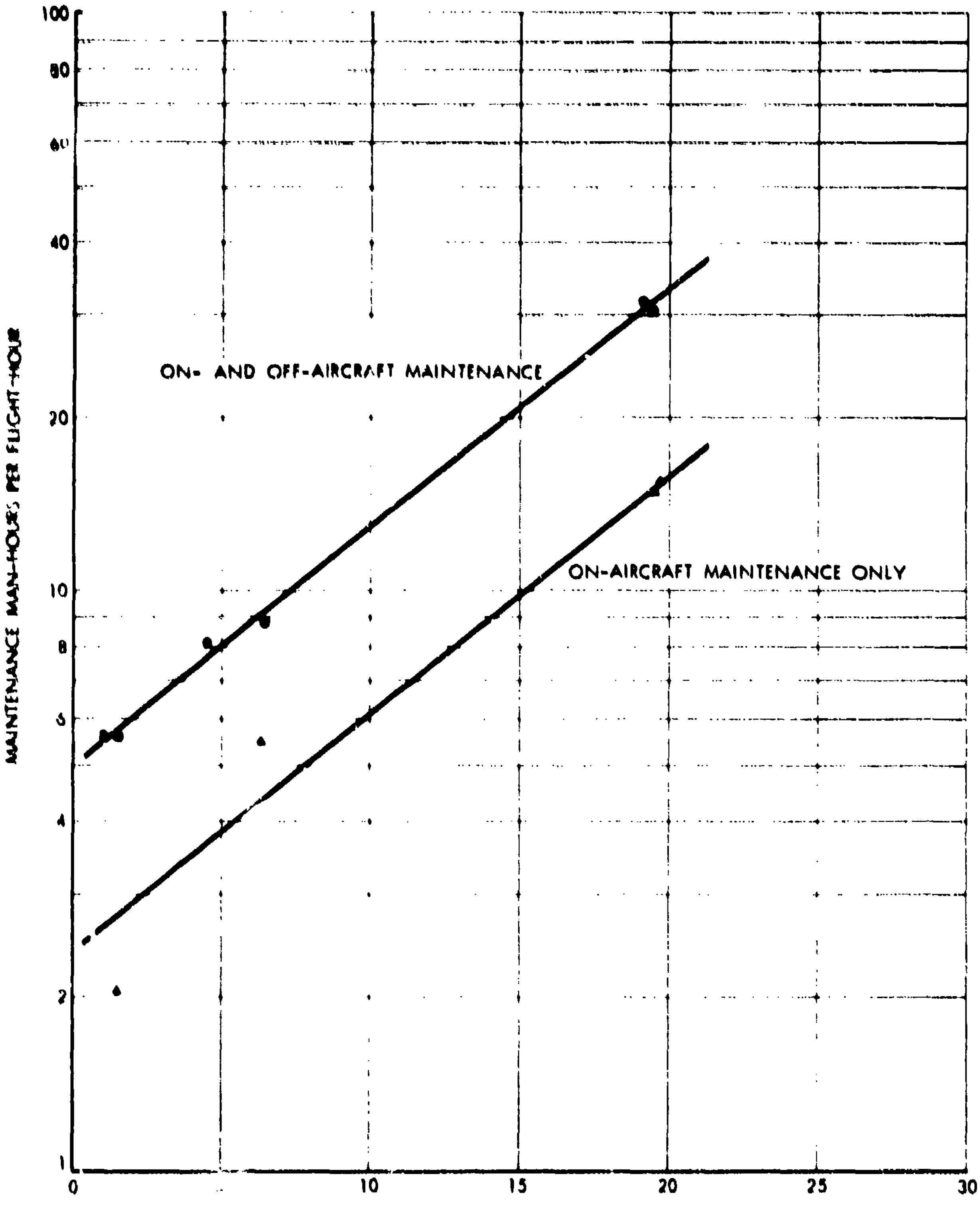

Figure 13. MMH/FH VERSUS EMPTY WEIGHT FOR ARMY HELICOPTERS

B. NAVY 3-M DATA

Navy aircraft maintenance data is reported under the Maintenance Material Management (3-M) reporting system, a computerized system operated by the Navy Fleet Material Support Office, Mechanicsburg, Pennsylvania. Data are submitted on all Navy aircraft in service use; the test period prior to service use is not covered. Data are published on both monthly and quarterly bases. The Navy advised against our use of its 3-M data before CY 1968, because they were less reliable than data for FYs 1968-73, which are reported herein.

Data are assembled by major operating command. For example, the UH-1N reports show separate data for the following operating commands:

FMFLANT (Fleet Marine Force Atlantic)
CNAP (Commander, Naval Air Force Pacific)
MARNFMF (Marine Non-FMF)
NATRA (Naval Air Training)
CNAL (Commander, Naval Air Force Atlantic).

Data for helicopters operating under combat conditions in Vietnam probably are not representative of normal noncombat operations. Accordingly, we excluded data from the Pacific commands in our use of the 3-M data.

The 3-M system permits the ready calculation of three R/M measures: (1) mean flight-hours between maintenance[1] actions (MFHBMA),[2] (2) mean flight-hours between failures[1] (MTBF), and (3) maintenance[1] man-hours per flight-hour (MMH/FH).[3] It is

---

[1] Reference [12] includes the following definitions:
Maintenance. All actions necessary for retaining an item in or restoring it to a specified condition.
Failure. The inability of an item to perform within previously specified limits.

[2] Unscheduled maintenance actions only.

[3] Unscheduled maintenance only at the organizational and the intermediate maintenance-activity levels.

also possible, with great effort, to obtain mission-abort rates; however, in our use of the 3-M data we developed only the first three R/M measures.

The 3-M data are coded by numerical work-unit codes (WUCs), which identify the various parts of the helicopter. This coding permits one to assemble data by helicopter system. We assembled data into the following systems: (1) airframe, (2) rotors and hubs, (3) gear boxes and drives, (4) power plant, (5) instruments, communication, and navigation, (6) weapon systems (where applicable), and (7) total. In many cases the weapon systems are responsible for relatively few maintenance actions, failures, and maintenance man-hours; in those cases the data for the weapon systems shown in the tables are not plotted on the graphs. 3-M data are available for five basic types of Navy helicopters: the H-1, H-2, H-3, H-46, and H-53.

1. The H-1

In Table 8 we have combined the data for all the single-engine types in this series except the AH-1G gunship (i.e., the UH-1D, UH-1E, UH-1H, UH-1L, TH-1L, and HH-1K models). Since all these models in Table 8 are quite similar, we feel that a more meaningful fleet average is obtained by combining these types rather than by considering them individually. Tables 9-11 present data for three other H-1 models in Navy service: the UH-1N, AH-1G, and AH-1J. The UH-1N and AH-1J are twin-engine models. These three are sufficiently different (from the H-1 models of Table 8) that we felt they should be treated separately. Using the data of Tables 8-11, the three R/M measures are plotted for the various H-1 models in Figures 14-25. Figures 14 and 16 indicate that the MTBMA and MMH/FH for the UH-1D/UH-1E/UH-1H/UH-1L/TH-1L/HH-1K fleet were fairly constant over the period 1968-7[illegible], while Figure 15 indicates that MTBF worsened somewhat. Figures 17-25 indicate that for the UH-1N, AH-1G, and AH-1J

helicopters, the measures of R/M worsened markedly over the three years these helicopters have been in service.[1]

The trends for the various components do not appear to differ systematically from the trends for the total aircraft. However, relative to the single-engine utility helicopter models, there does appear to be a worsening in R/M characteristics of the models shown separately. In general, the ranking by R/M characteristics is (1) UH-1D/UH-1E/UH-1H/UH-1L/TH-1L/HH-1K (best), (2) UH-1N, (3) AG-1G, (4) AH-1J (worst). This ranking is due mainly to the twin engines of the UH-1N and AH-1J and the weapon systems of the AH models.

[1] In some cases when a helicopter was entering service and the data for these years were not meaningful, they were not plotted.

Table 8. NAVY 3-M DATA FOR UH-1D, UH-1E, UH-1H, UH-1L, TH-1L, and HH-1K MODELS

AIRFRAME — AIRCRAFT H-1(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	8380	1446	5.80	759	11.04	4313	.51
1969	18322	3986	4.60	1305	14.04	12356	.67
1970	32389	7766	4.17	2755	11.76	28417	.88
1971	45565	8152	5.59	3310	13.77	27866	.61
1972	53381	10069	5.30	5888	9.07	35830	.67
1973	45250	9593	4.72	6066	7.46	35366	.78

ROTORS AND HUBS(MAIN/TAIL) — AIRCRAFT H-1(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	8380	672	12.47	296	28.31	3379	.40
1969	18322	1044	17.55	455	40.27	3475	.19
1970	32389	2497	12.97	1211	26.75	10682	.33
1971	45565	2489	18.31	1295	35.19	12496	.27
1972	53381	3610	14.79	1886	28.30	16398	.31
1973	45250	3990	11.34	2416	18.73	17988	.40

GEAR BOXES AND DRIVES — AIRCRAFT H-1(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	8380	227	36.92	126	66.51	907	.11
1969	18322	819	22.37	321	57.08	3327	.18
1970	32389	1472	22.00	571	56.72	7437	.23
1971	45565	1374	33.16	599	76.07	6604	.15
1972	53381	1902	28.07	1073	49.75	8546	.16
1973	45250	1553	29.14	980	46.17	7108	.16

POWER PLANT — AIRCRAFT H-1(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	8380	471	17.79	260	32.23	2465	.29
1969	18322	1522	12.04	575	31.86	5740	.31
1970	32389	3074	10.54	1170	27.68	11865	.37
1971	45565	2999	15.19	1357	33.58	12236	.27
1972	53381	3608	14.80	2139	24.96	14889	.28
1973	45250	3200	14.14	2162	20.93	12406	.27

(continued on next page)

Table 8 (continued)

INSTRUMENT,COMM AND NAV — AIRCRAFT H-1(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	8380	1625	5.16	810	10.35	5417	.65
1969	18322	2870	6.38	608	30.13	6900	.38
1970	32389	5174	6.26	2245	14.43	23394	.72
1971	45565	6372	7.15	2767	16.47	24717	.54
1972	53381	6630	8.05	3718	14.36	25165	.47
1973	45250	5149	8.79	2995	15.11	24008	.53

WEAPON SYSTEMS — AIRCRAFT H-1(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	8380	13	644.62	10	838.00	50	.01
1969	18322	33	555.21	11	1665.64	84	.00
1970	32389	64	506.08	33	981.48	245	.01
1971	45565	181	251.74	89	511.97	500	.01
1972	53381	128	417.04	72	741.40	335	.01
1973	45250	105	430.95	49	923.47	348	.01

* * * T O T A L * * *

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	8380	4454	1.88	2261	3.71	16531	1.97
1969	18322	10274	1.78	3275	5.59	31882	1.74
1970	32389	20047	1.62	7985	4.06	81980	2.53
1971	45565	21567	2.11	9417	4.84	84509	1.85
1972	53381	25947	2.06	14776	3.61	101143	1.89
1973	45250	23590	1.92	14668	3.08	97222	2.15

Table 9. NAVY 3-M DATA FOR THE UH-1N

AIRFRAME — AIRCRAFT UH-1N

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	0	0	0.00	0	0.00	0	0.00
1969	0	0	0.00	0	0.00	0	0.00
1970	0	0	0.00	0	0.00	0	0.00
1971	2082	343	6.07	191	10.90	1009	.48
1972	9911	2363	4.19	1245	7.96	6556	.66
1973	15790	4160	3.80	2322	6.80	13649	.86

ROTORS AND HUBS(MAIN/TAIL) — AIRCRAFT UH-1N

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	0	0	0.00	0	0.00	0	0.00
1969	0	0	0.00	0	0.00	0	0.00
1970	0	0	0.00	0	0.00	0	0.00
1971	2082	47	44.30	27	77.11	146	.07
1972	9911	551	17.99	246	40.29	1113	.11
1973	15790	1400	11.28	546	28.92	3998	.25

GEAR BOXES AND DRIVES — AIRCRAFT UH-1N

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	0	0	0.00	0	0.00	0	0.00
1969	0	0	0.00	0	0.00	0	0.00
1970	0	0	0.00	0	0.00	0	0.00
1971	2082	34	61.24	21	99.14	243	.12
1972	9911	319	31.07	190	52.16	934	.09
1973	15790	667	23.67	432	36.55	2935	.19

POWER PLANT — AIRCRAFT UH-1N

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	0	0	0.00	0	0.00	0	0.00
1969	0	0	0.00	0	0.00	0	0.00
1970	0	0	0.00	0	0.00	0	0.00
1971	2082	218	9.55	154	13.52	619	.30
1972	9911	971	10.21	645	15.37	7108	.72
1973	15790	2278	6.93	1473	10.72	14447	.91

(continued on next page)

Table 9 (continued)

INSTRUMENT,COMM AND NAV — AIRCRAFT UH-1N

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	0	0	0.00	0	0.00	0	0.00
1969	0	0	0.00	0	0.00	0	0.00
1970	0	0	0.00	0	0.00	0	0.00
1971	2082	308	6.76	95	21.92	714	.34
1972	9911	1586	6.25	725	13.67	6158	.62
1973	15790	2851	5.54	1413	11.17	10285	.65

WEAPON SYSTEMS — AIRCRAFT UH-1N

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	0	0	0.00	0	0.00	0	0.00
1969	0	0	0.00	0	0.00	0	0.00
1970	0	0	0.00	0	0.00	0	0.00
1971	2082	2	1041.00	1	2082.00	5	.00
1972	9911	46	215.46	16	619.44	59	.01
1973	15790	21	751.90	7	2255.71	34	.00

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YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	0	0	0.00	0	0.00	0	0.00
1969	0	0	0.00	0	0.00	0	0.00
1970	0	0	0.00	0	0.00	0	0.00
1971	2082	952	2.19	489	4.26	2736	1.31
1972	9911	5836	1.70	3067	3.23	21928	2.21
1973	15790	11377	1.39	6193	2.55	45348	2.87

Table 10. NAVY 3-M DATA FOR THE AH-1G

AIRFRAME — AIRCRAFT AH-1G

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	0	0	0.00	0	0.00	0	0.00
1969	0	0	0.00	0	0.00	0	0.00
1970	0	0	0.00	0	0.00	0	0.00
1971	383	42	9.12	28	13.68	109	.28
1972	1214	289	4.20	159	7.64	1207	.99
1973	1362	531	2.56	307	4.44	1561	1.15

ROTORS AND HUBS(MAIN/TAIL) — AIRCRAFT AH-1G

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	0	0	0.00	0	0.00	0	0.00
1969	0	0	0.00	0	0.00	0	0.00
1970	0	0	0.00	0	0.00	0	0.00
1971	383	11	34.82	7	54.71	29	.08
1972	1214	62	19.58	34	35.71	345	.28
1973	1362	91	14.97	64	21.28	403	.30

GEAR BOXES AND DRIVES — AIRCRAFT AH-1G

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	0	0	0.00	0	0.00	0	0.00
1969	0	0	0.00	0	0.00	0	0.00
1970	0	0	0.00	0	0.00	0	0.00
1971	383	12	31.92	7	54.71	21	.05
1972	1214	52	23.35	28	43.36	315	.26
1973	1362	70	19.46	44	30.95	169	.12

POWER PLANT — AIRCRAFT AH-1G

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	0	0	0.00	0	0.00	0	0.00
1969	0	0	0.00	0	0.00	0	0.00
1970	0	0	0.00	0	0.00	0	0.00
1971	383	5	76.60	5	76.60	7	.02
1972	1214	60	20.23	36	33.72	205	.17
1973	1362	190	7.17	118	11.54	444	.33

(continued on next page)

Table 10 (continued)

INSTRUMENT,COMM AND NAV AIRCRAFT AH-1G

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	0	0	0.00	0	0.00	0	0.00
1969	0	0	0.00	0	0.00	0	0.00
1970	0	0	0.00	0	0.00	0	0.00
1971	383	43	8.91	21	18.24	136	.36
1972	1214	200	6.07	98	12.39	727	.60
1973	1362	301	4.52	118	11.54	897	.66

WEAPON SYSTEMS AIRCRAFT AH-1G

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	0	0	0.00	0	0.00	0	0.00
1969	0	0	0.00	0	0.00	0	0.00
1970	0	0	0.00	0	0.00	0	0.00
1971	383	2	191.50	1	383.00	4	.01
1972	1214	39	31.13	14	86.71	133	.11
1973	1362	56	24.32	16	85.12	166	.12

* * * T O T A L * * *

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	0	0	0.00	0	0.00	0	0.00
1969	0	0	0.00	0	0.00	0	0.00
1970	0	0	0.00	0	0.00	0	0.00
1971	383	115	3.33	69	5.55	306	.80
1972	1214	702	1.73	369	3.29	2932	2.42
1973	1362	1239	1.10	667	2.04	3640	2.67

Table 11. NAVY 3-M DATA FOR THE AH-1J

AIRFRAME — AIRCRAFT AH-1J

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	0	0	0.00	0	0.00	0	0.00
1969	0	0	0.00	0	0.00	0	0.00
1970	13	13	1.00	7	1.86	21	1.62
1971	2216	764	2.90	403	5.50	2141	.97
1972	3685	742	4.97	418	8.82	2013	.55
1973	6524	4452	1.47	2400	2.72	11348	1.74

ROTORS AND HUBS(MAIN/TAIL) — AIRCRAFT AH-1J

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	0	0	0.00	0	0.00	0	0.00
1969	0	0	0.00	0	0.00	0	0.00
1970	13	0	0.00	0	0.00	0	0.00
1971	2216	137	16.18	91	24.35	739	.33
1972	3685	235	15.68	146	25.24	1280	.35
1973	6524	873	7.47	410	15.91	4262	.64

GEAR BOXES AND DRIVES — AIRCRAFT AH-1J

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	0	0	0.00	0	0.00	0	0.00
1969	0	0	0.00	0	0.00	0	0.00
1970	13	1	13.00	0	0.00	2	.15
1971	2216	69	32.12	41	54.05	343	.15
1972	3685	157	23.47	100	36.85	830	.23
1973	6524	695	9.39	429	15.21	3689	.57

POWER PLANT — AIRCRAFT AH-1J

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	0	0	0.00	0	0.00	0	0.00
1969	0	0	0.00	0	0.00	0	0.00
1970	13	9	1.44	6	2.17	9	.69
1971	2216	318	6.97	212	10.45	3127	1.41
1972	3685	399	9.24	285	12.93	2801	.76
1973	6524	2109	3.09	1306	5.00	9097	1.39

(continued on next page)

Table 11 (continued)

INSTRUMENT,COMM AND NAV — AIRCRAFT AH-1J

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	0	0	0.00	0	0.00	0	0.00
1969	0	0	0.00	0	0.00	0	0.00
1970	13	10	1.30	4	3.25	14	1.08
1971	2216	509	4.35	249	8.90	1216	.55
1972	3685	719	5.13	383	9.62	3593	.98
1973	6524	2192	2.98	1053	6.20	6194	.95

WEAPON SYSTEMS — AIRCRAFT AH-1J

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	0	0	0.00	0	0.00	0	0.00
1969	0	0	0.00	0	0.00	0	0.00
1970	13	1	13.00	0	0.00	1	.08
1971	2216	94	23.57	37	59.89	266	.12
1972	3685	183	20.14	85	43.35	705	.19
1973	6524	1048	6.23	547	11.93	2960	.45

* * * T O T A L * * *

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	0	0	0.00	0	0.00	0	0.00
1969	0	0	0.00	0	0.00	0	0.00
1970	13	34	.38	17	.76	47	3.62
1971	2216	1891	1.17	1033	2.15	7832	3.53
1972	3685	2435	1.51	1417	2.60	11222	3.05
1973	6524	11369	.57	6145	1.06	37490	5.75

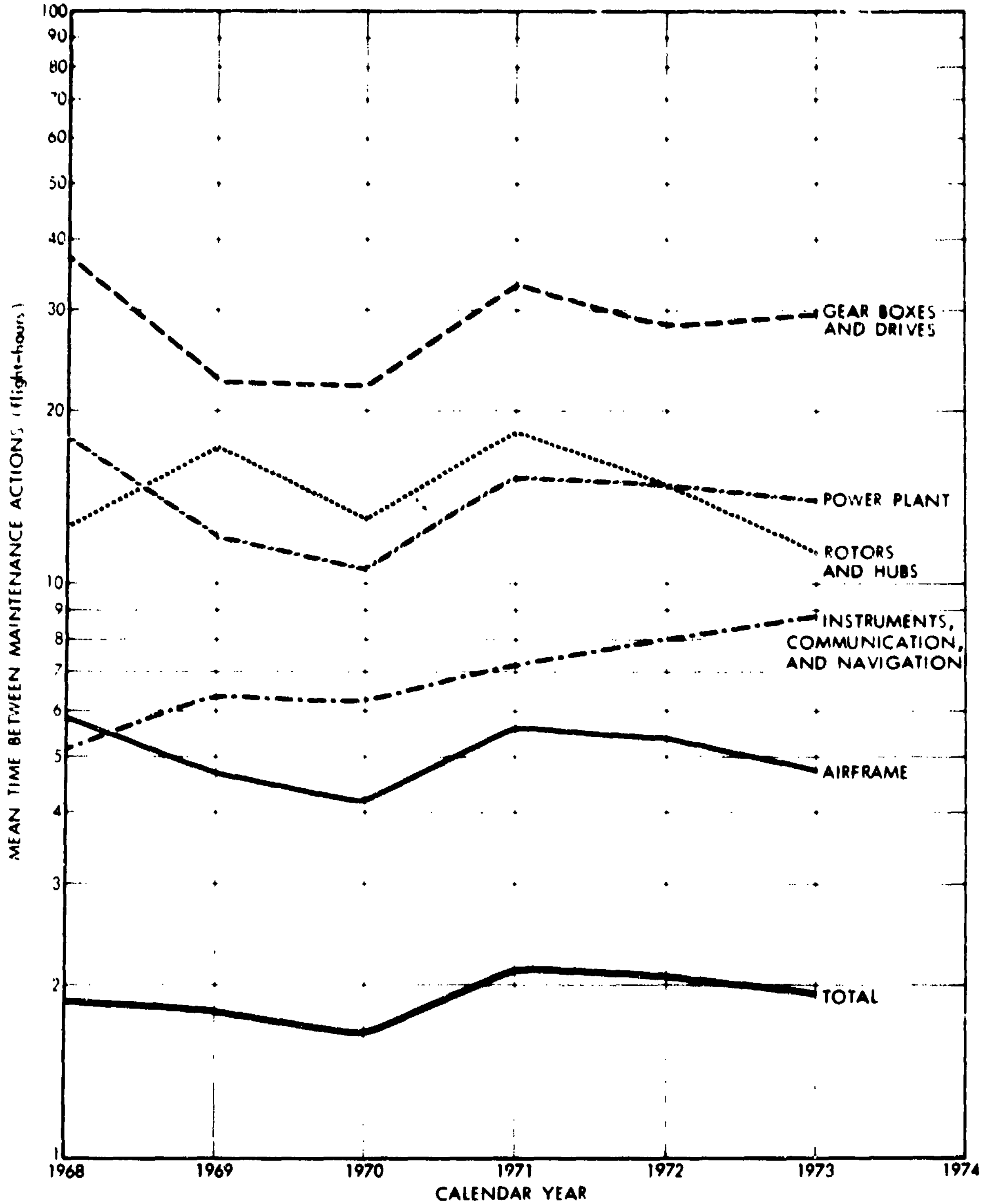

Figure 14. MTBMA FOR THE NAVY SINGLE-ENGINE UH-1/HH-1/TH-1 SERIES

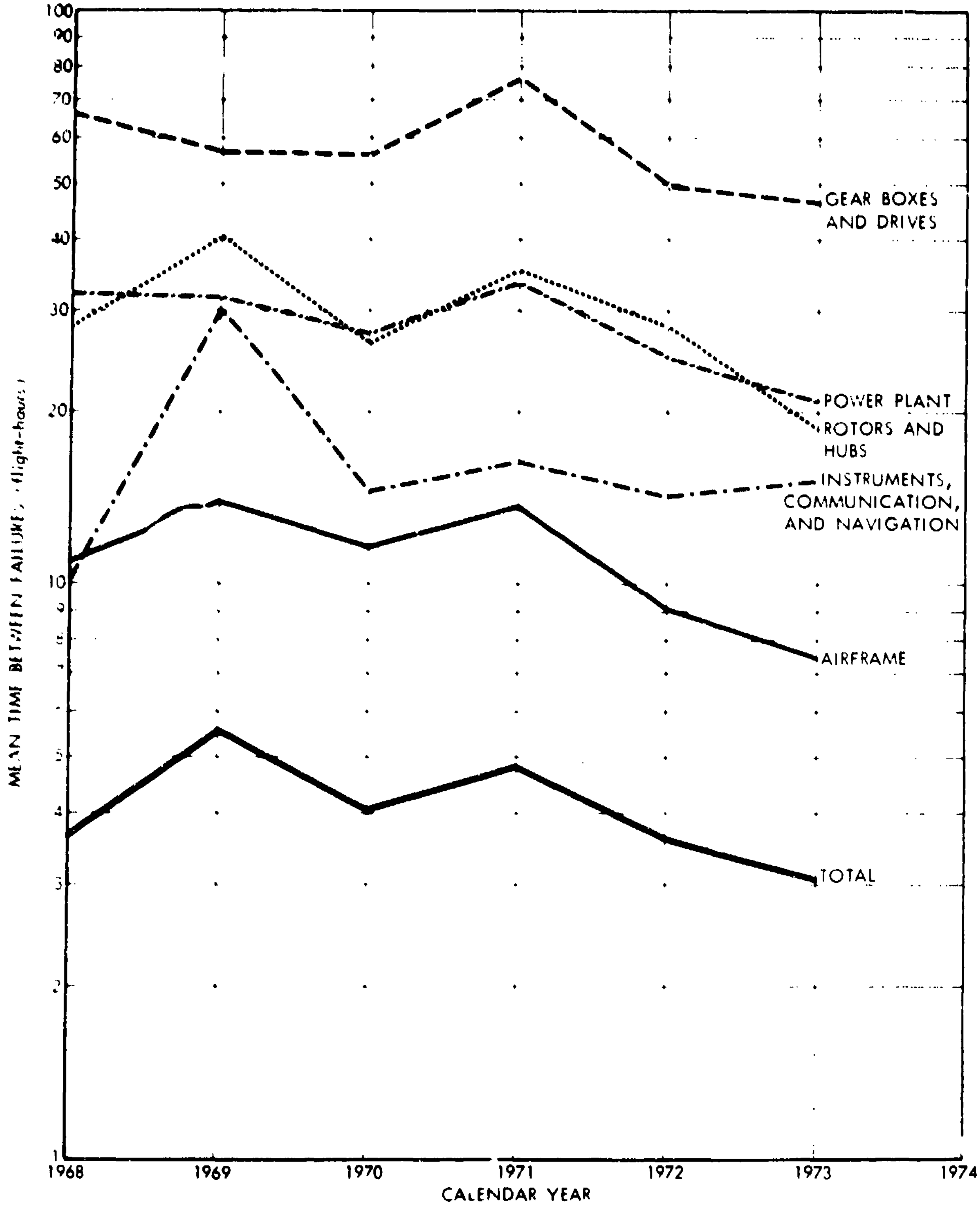

Figure 15. MTBF VERSUS YEAR FOR THE NAVY SINGLE-ENGINE UH-1/HH-1/TH-1 SERIES

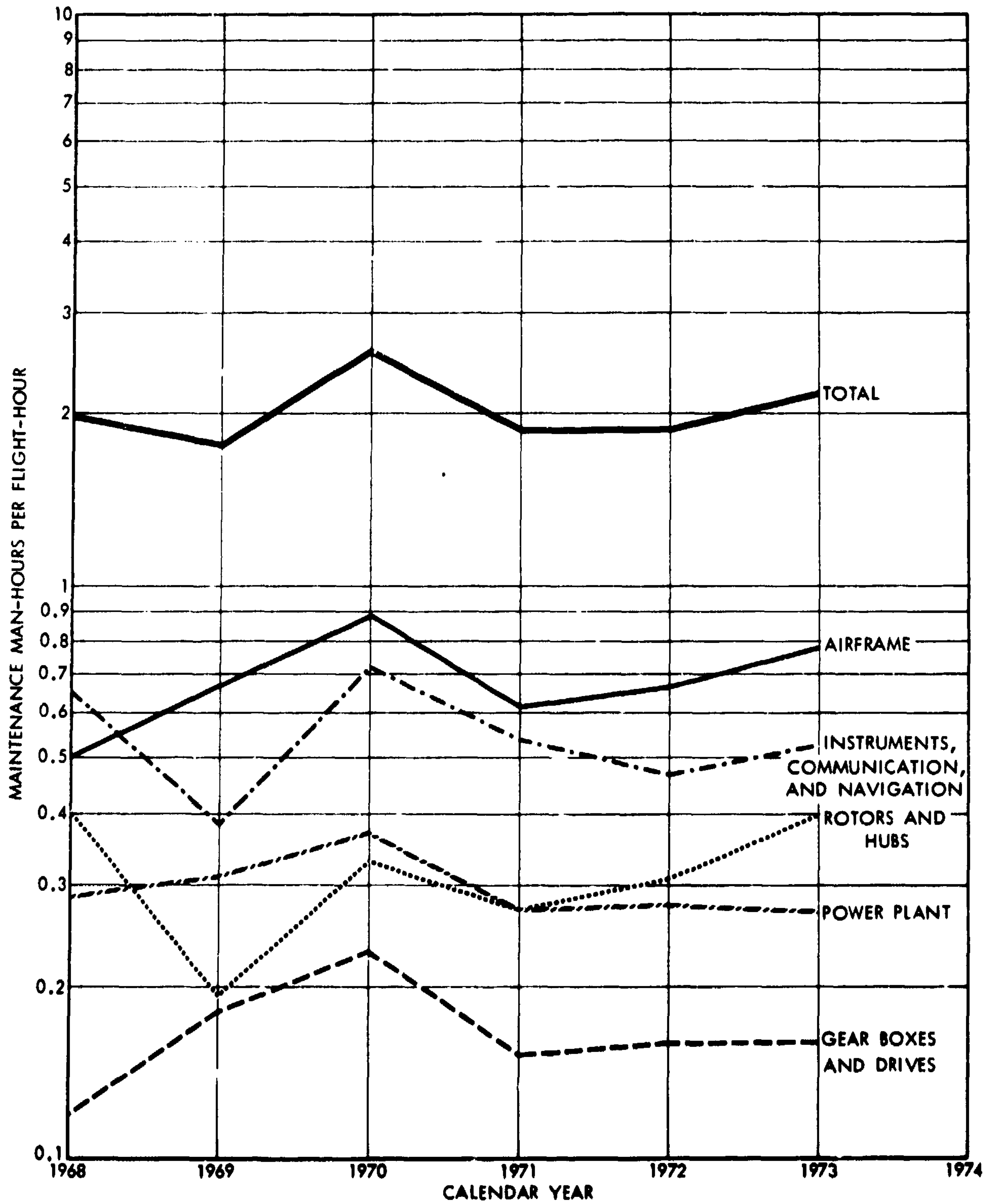

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Figure 16. MMH/FH FOR THE NAVY SINGLE-ENGINE UH-1/HH-1/TH-1 SERIES

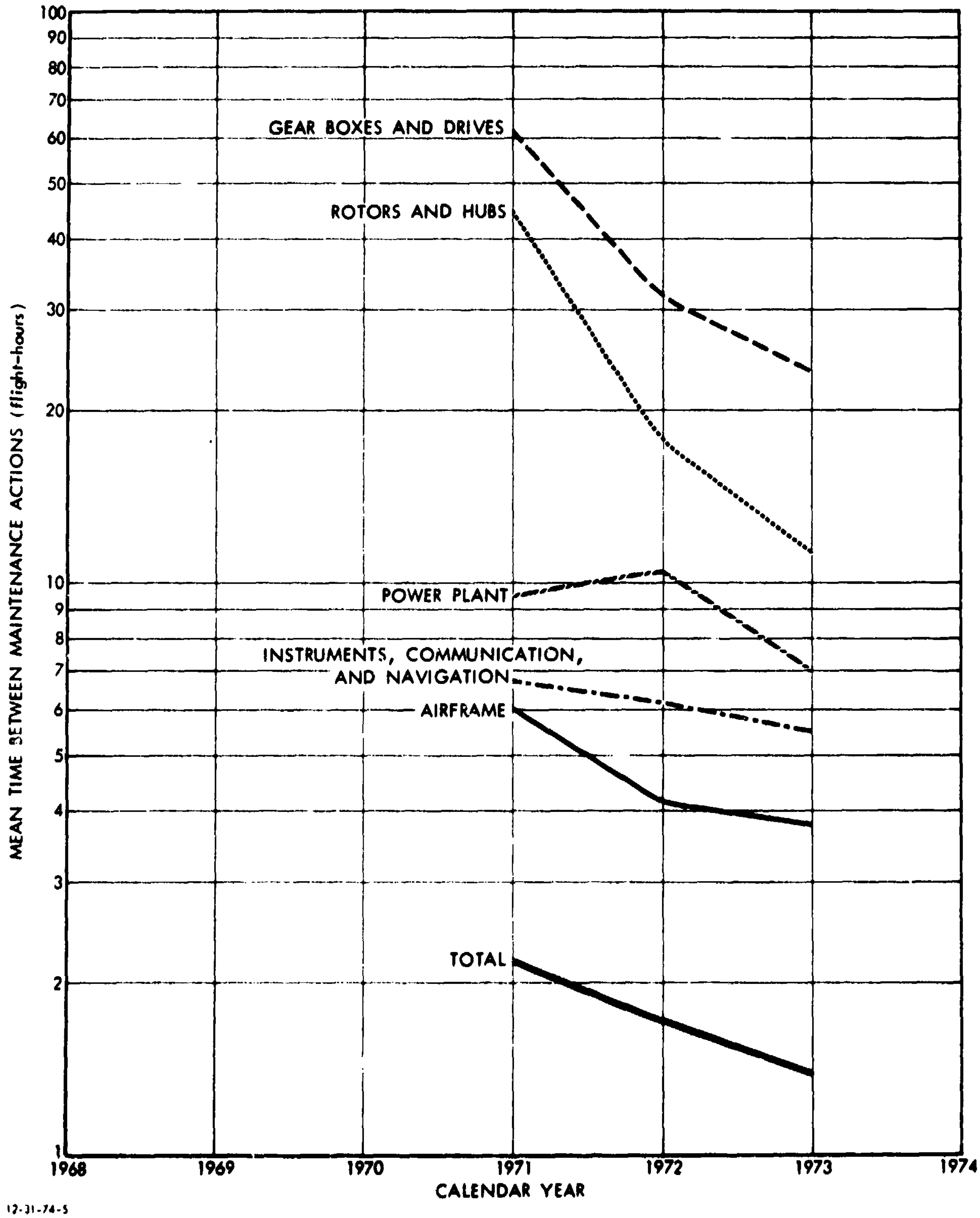

Figure 17. MTBMA FOR THE NAVY UH-1N

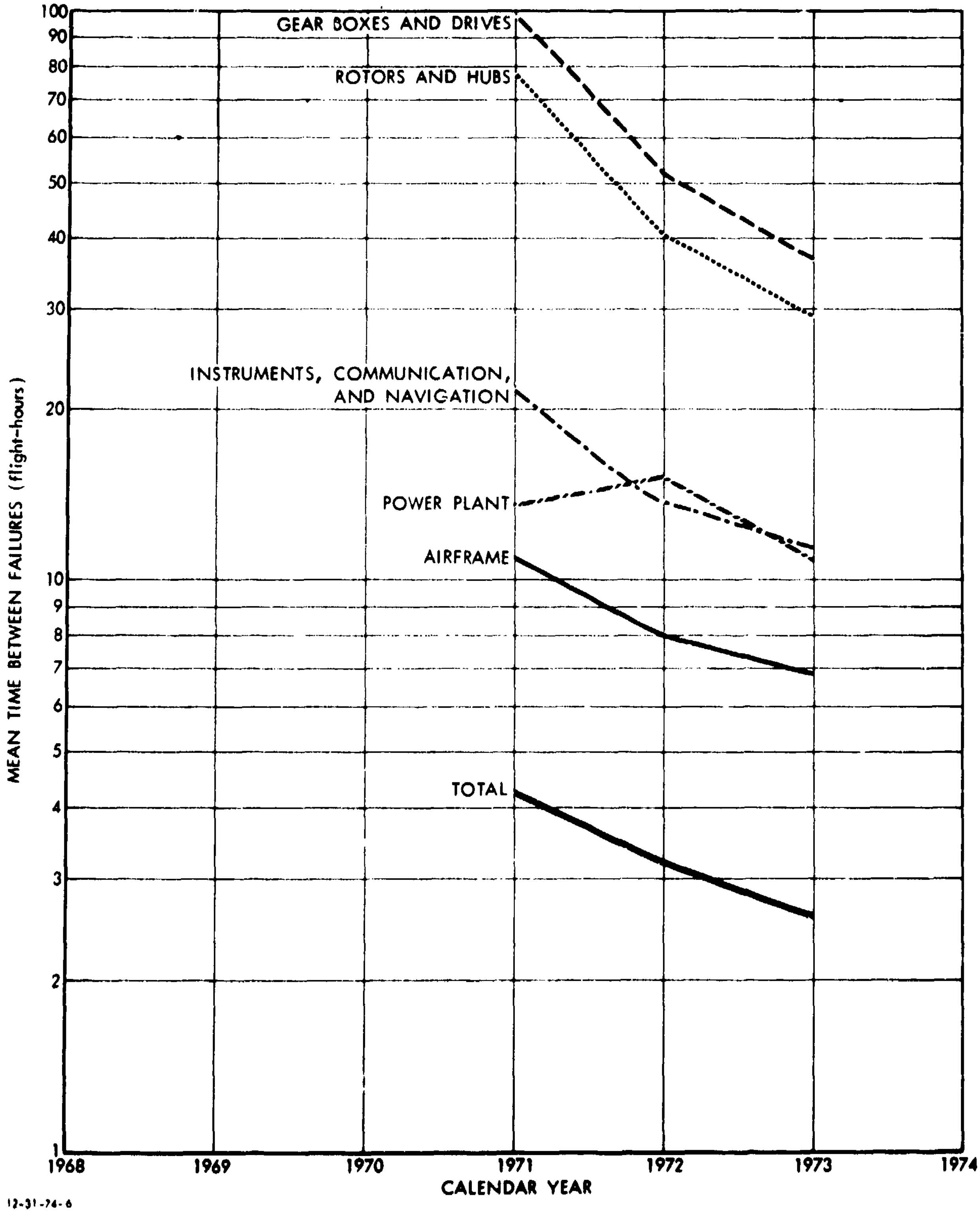

Figure 18. MTBF VERSUS YEAR FOR THE NAVY SINGLE-ENGINE UH-1N

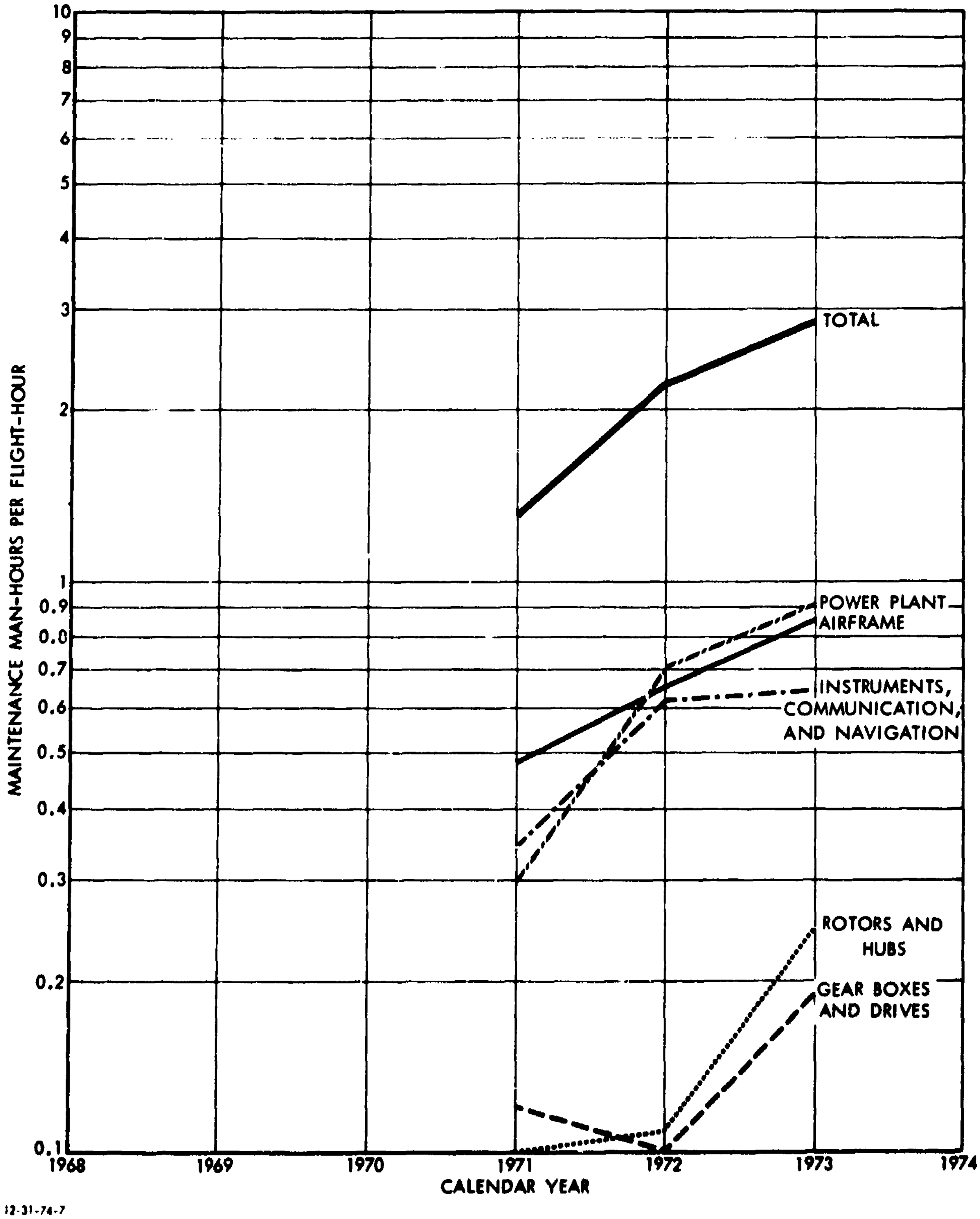

Figure 19. MMH/FH FOR THE NAVY UH-1N

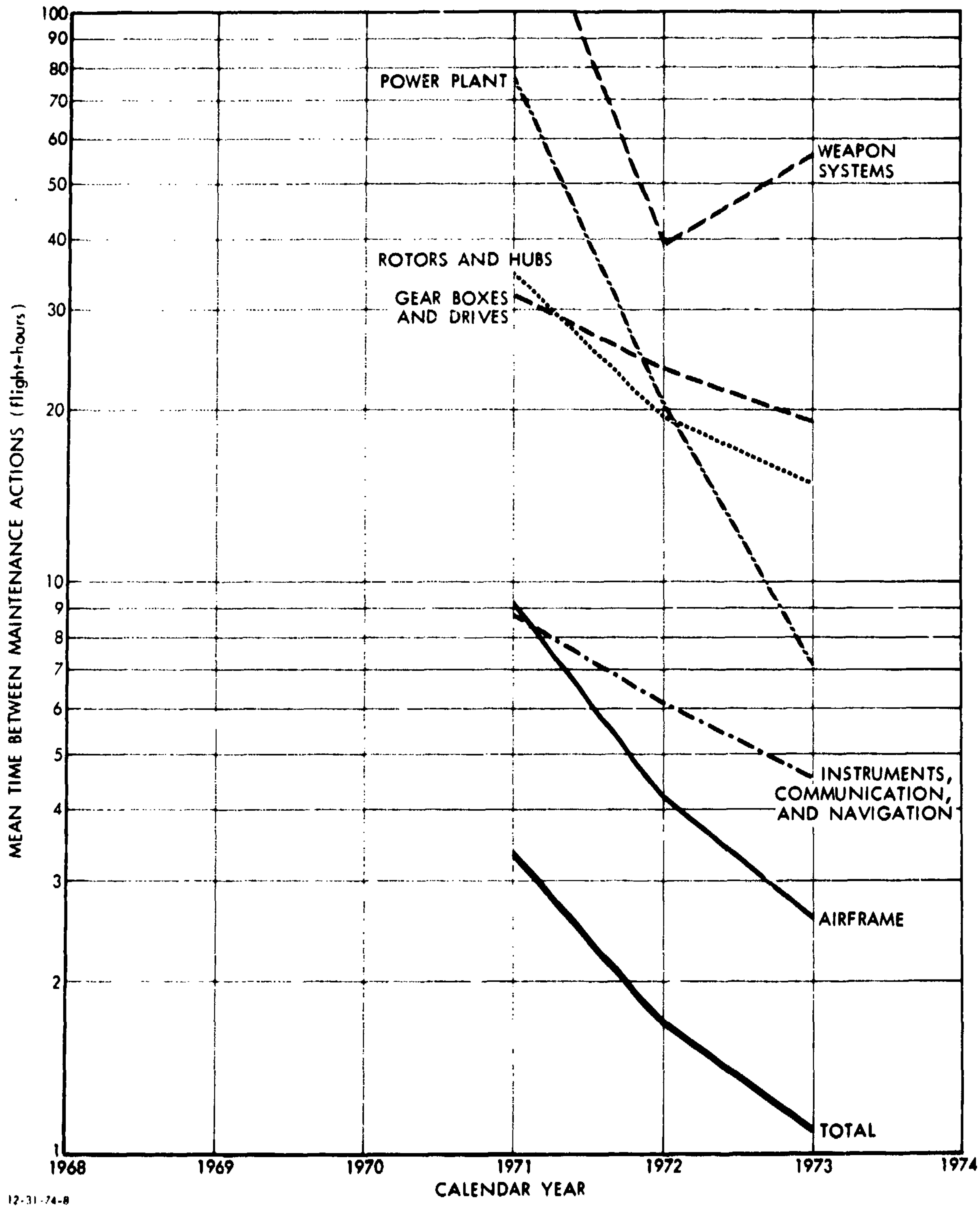

Figure 20. MTBMA FOR THE NAVY AH-1G

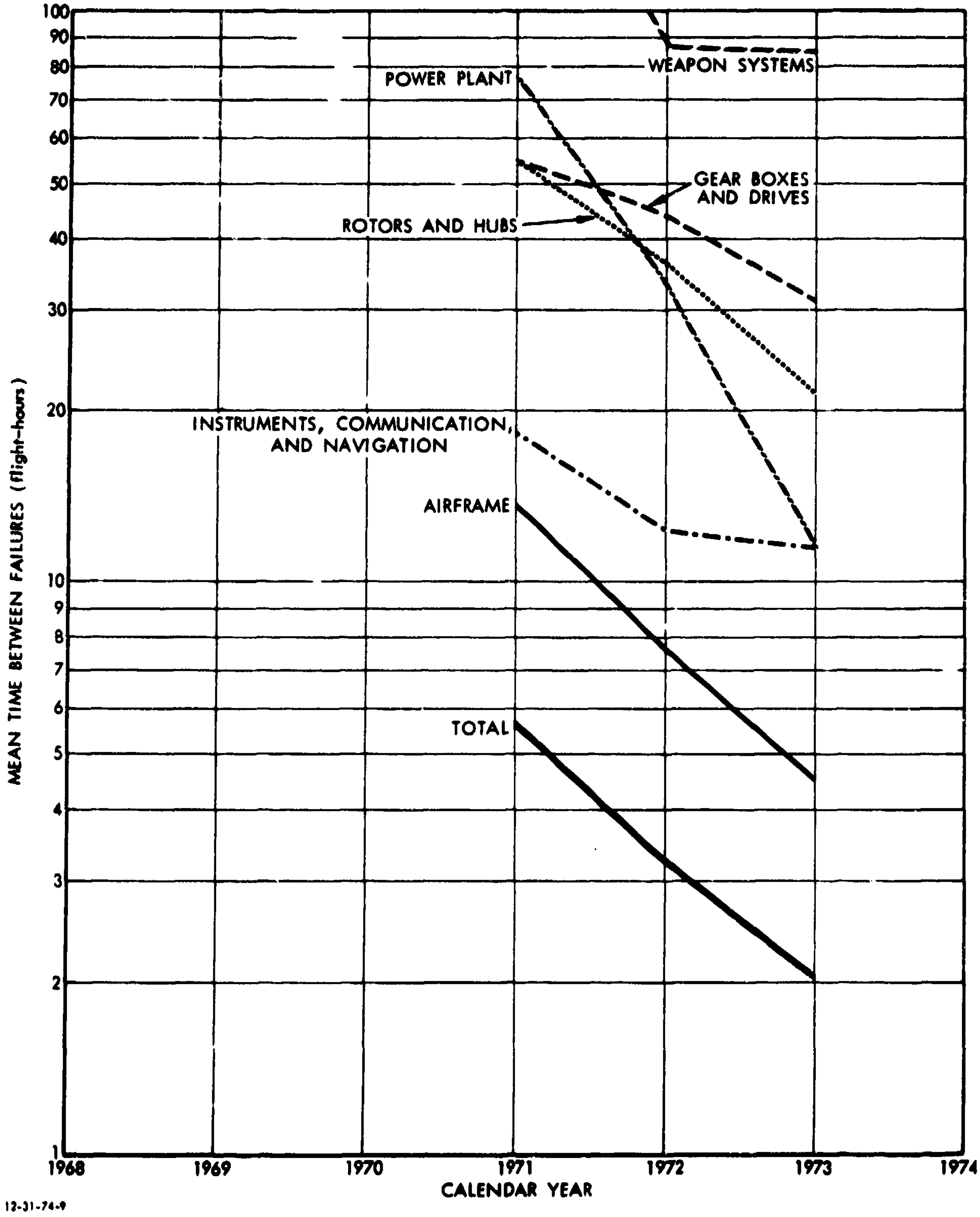

Figure 21. MTBF VERSUS YEAR FOR THE NAVY AH-1G

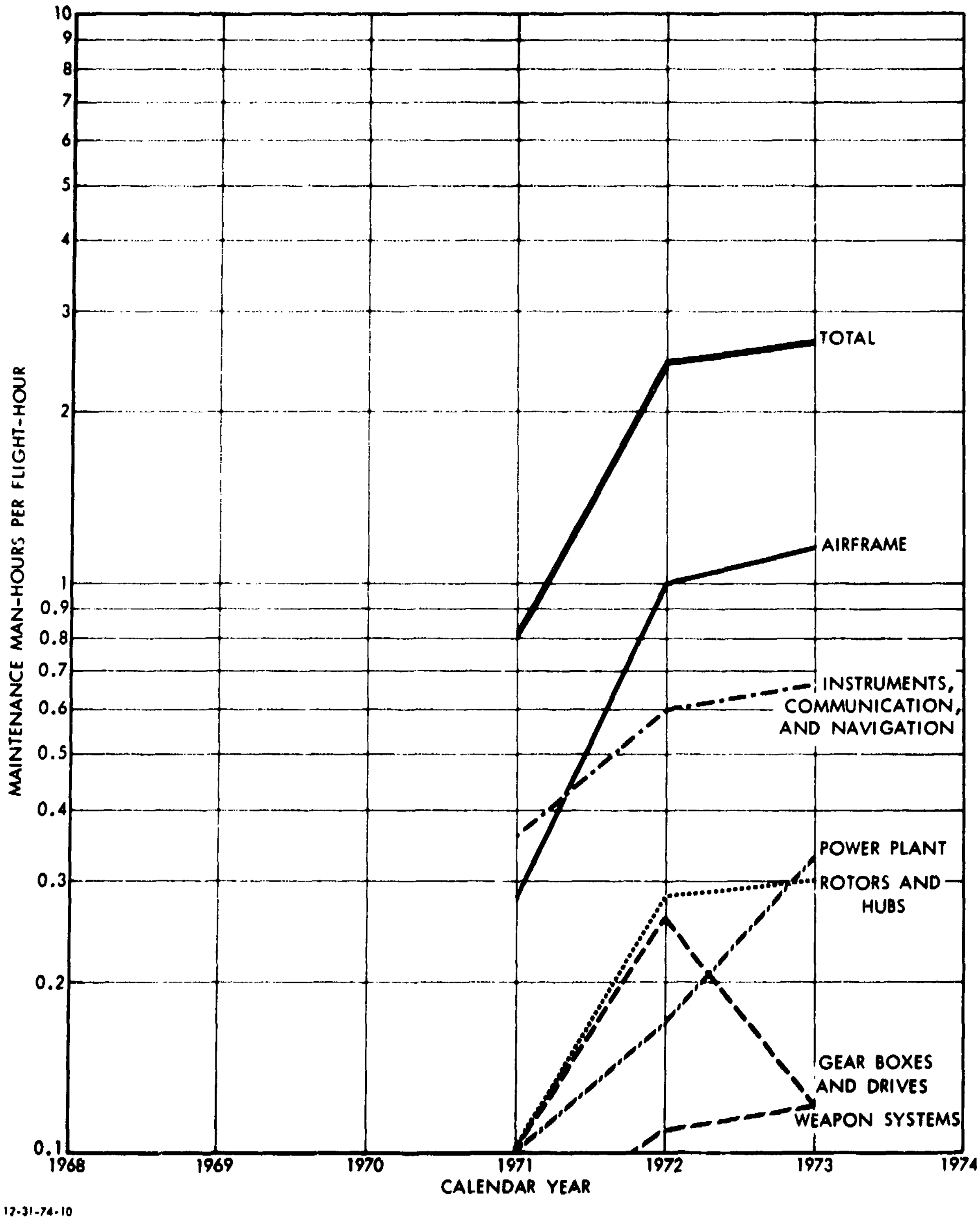

Figure 22. MMH/FH FOR THE NAVY AH-1G

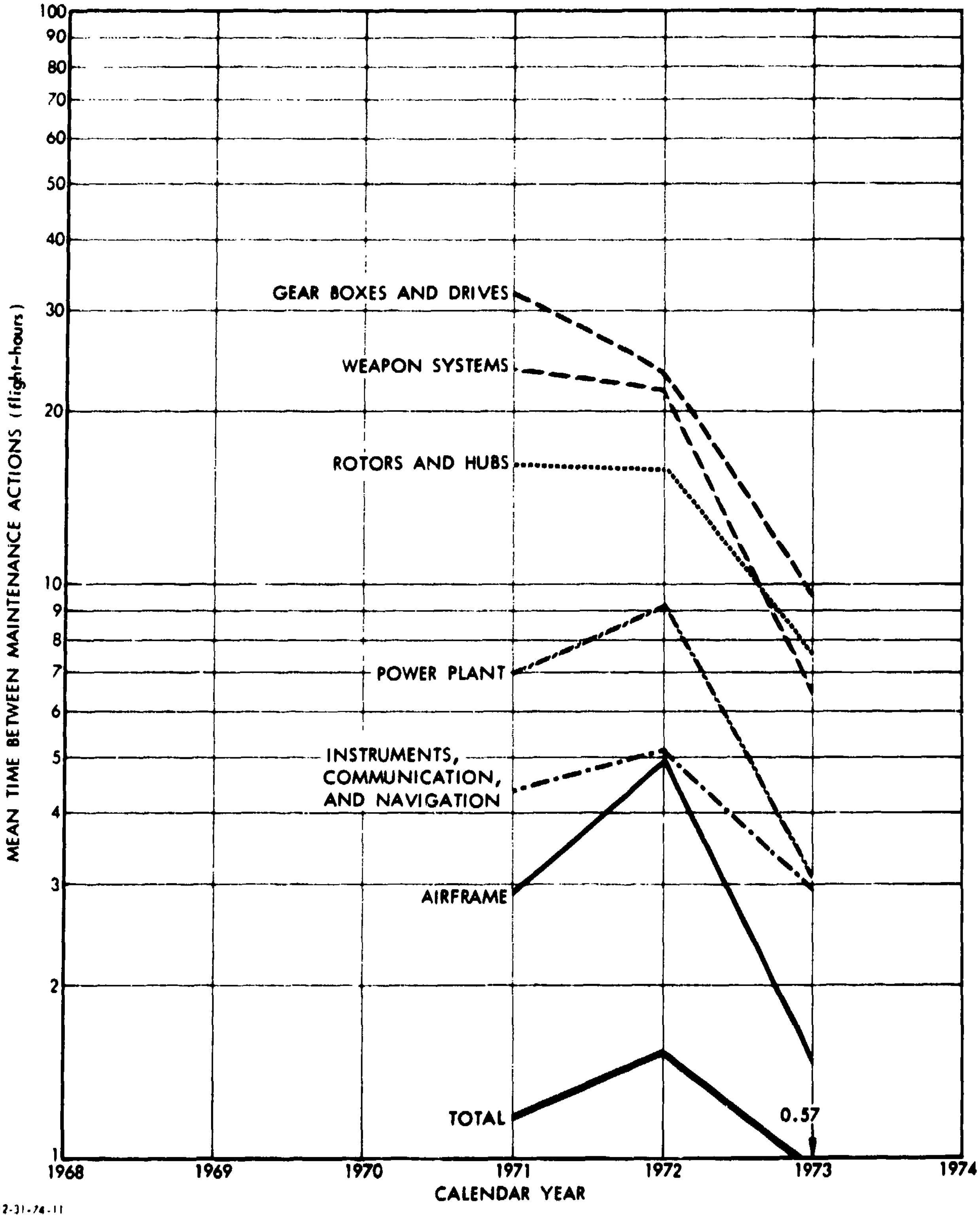

Figure 23. MTBMA FOR THE NAVY AH-1J

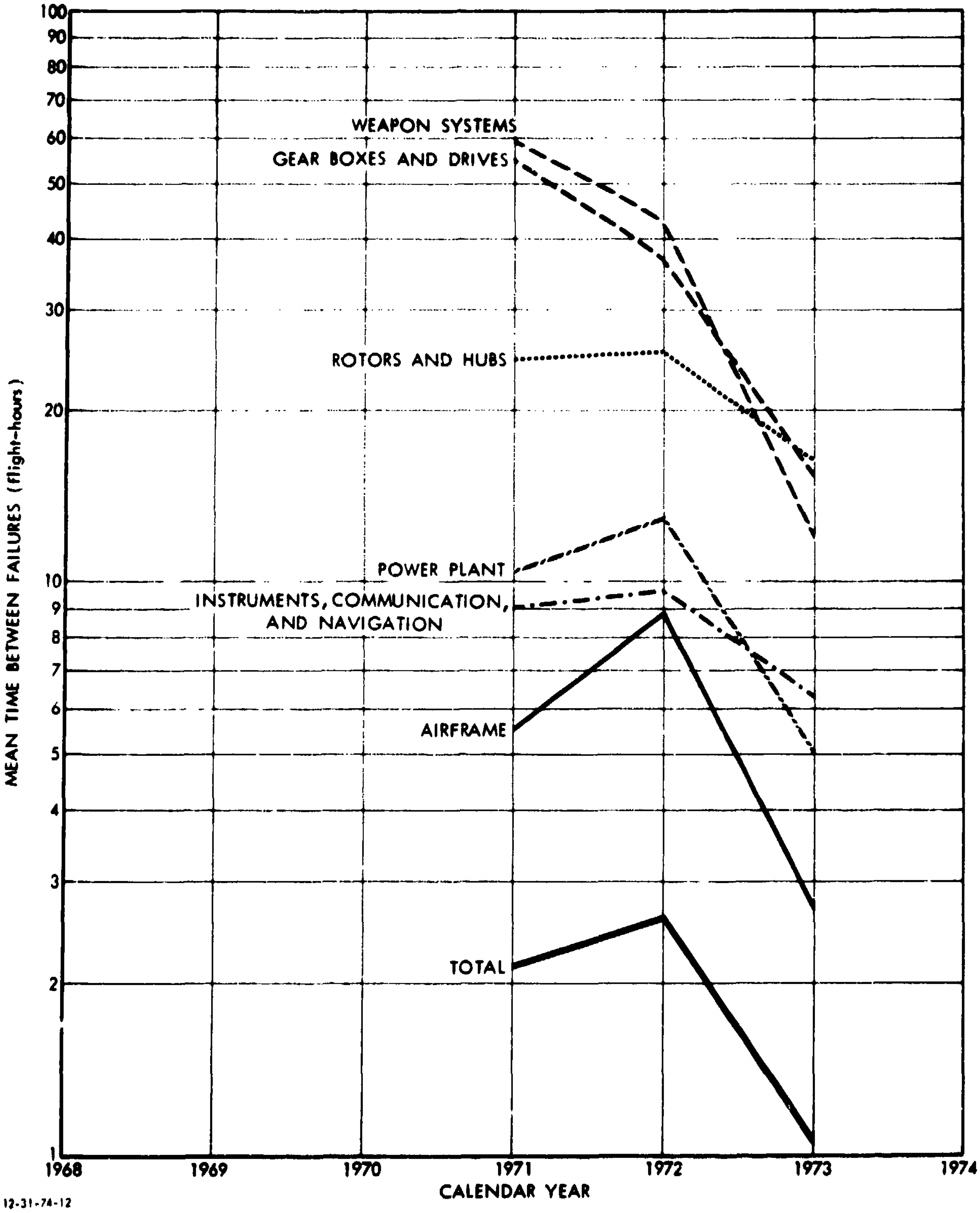

Figure 24. MTBF VERSUS YEAR FOR THE NAVY AH-1J

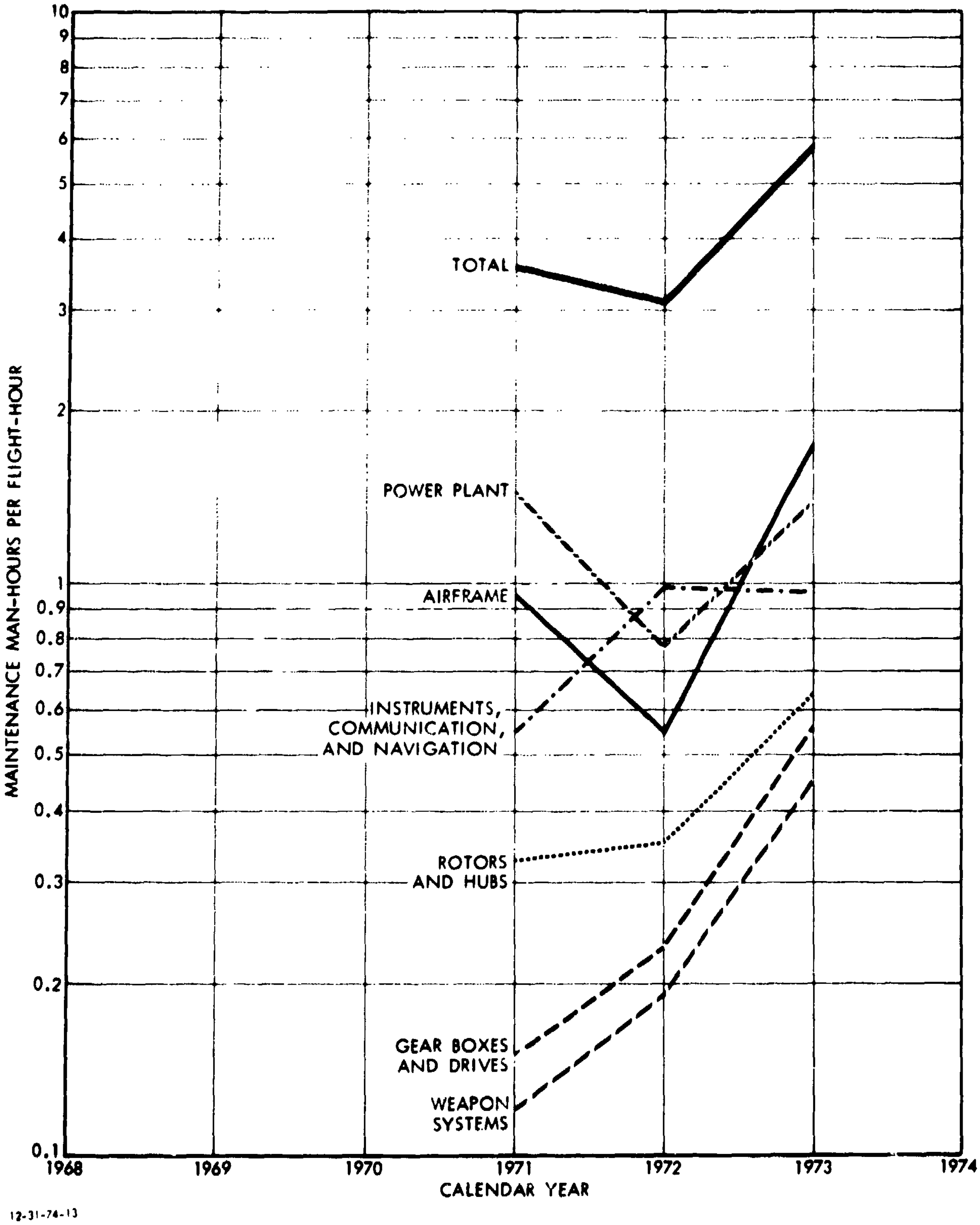

Figure 25. MMH/FH FOR THE NAVY AH-1J

2. The H-2

The U.S. Navy is the only operator of the H-2. A total of 190 of them were built--each with a single T-58 engine. Eighty-eight were UH-2A aircraft and 102 were UH-2B aircraft, which differed only in the noninstallation of certain electronic navigation equipment. Starting in 1967, the survivors of these 190 aircraft were all converted to twin T-58 engines and were redesignated as the UH-2C, HH-2C, HH-2D, SH-2D, and SH-2F. We first segregated the 3-M data for the H-2's into three groups: (1) the UH-2A and UH-2B; (2) the UH-2C, HH-2C, and HH-2D; and (3) the SH-2D and SH-2F. However, the three R/M measures for these three groups were all quite similar in total and by component, both in levels of R/M and in trends over time. Accordingly, in Table 12 and Figures 26-28, we have aggregated data for all the H-2 aircraft. Figures 26 and 27 indicate that MTBMA and MTBF have both worsened somewhat over time, while Figure 28 indicates that MMH/FH has remained approximately constant. The trends for the various components do not appear to differ systematically from the trends for the total aircraft.

Compared with the other Navy helicopter types, the H-2 R/M characteristics are poor, particularly relative to the H-1 aircraft, which are approximately the same size. There are probably several causes contributing to this result:

- The H-2 has generally been operated in detachments of one or a few aircraft. Economies of scale have thus been lacking in their operating environment.
- Fewer H-2 aircraft than any of the other types were built. Accordingly, the economic incentives to introduce product improvements have not been as great as for the other types.
- Insofar as years of experience and production quantities are concerned, Kaman is somewhat behind the other manufacturers.

Table 12. NAVY 3-M DATA FOR ALL H-2 MODELS

AIRFRAME — AIRCRAFT H-2(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	13103	10988	1.19	5662	2.31	46113	3.52
1969	3121	3120	1.00	1404	2.22	13599	4.36
1970	8418	12053	.70	5161	1.63	23395	2.78
1971	8412	10836	.78	5466	1.54	25341	3.01
1972	10100	13894	.73	7507	1.35	32547	3.22
1973	12185	13986	.87	7287	1.67	35755	2.93

ROTORS AND HUBS(MAIN/TAIL) — AIRCRAFT H-2(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	13103	3838	3.41	2227	5.88	15760	1.20
1969	3121	996	3.13	570	5.48	4919	1.58
1970	8418	3353	2.51	1692	4.98	7976	.95
1971	8412	3395	2.48	1932	4.35	10271	1.22
1972	10100	4297	2.35	2512	4.02	12804	1.27
1973	12185	4587	2.66	2827	4.31	16752	1.37

GEAR BOXES AND DRIVES — AIRCRAFT H-2(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	13103	1778	7.37	947	13.84	8798	.67
1969	3121	427	7.31	231	13.51	2747	.88
1970	8418	1667	5.05	879	9.58	4572	.54
1971	8412	1290	6.52	711	11.83	3667	.44
1972	10100	1846	5.47	1188	8.50	7697	.76
1973	12185	2077	5.87	1227	9.93	9633	.79

POWER PLANT — AIRCRAFT H-2(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	13103	2085	6.28	1091	12.01	15804	1.21
1969	3121	568	5.49	296	10.54	3062	.98
1970	8418	2583	3.26	1274	6.61	11164	1.33
1971	8412	2937	2.86	1605	5.24	12994	1.54
1972	10100	3664	2.76	2210	4.57	13650	1.35
1973	12185	3853	3.16	2295	5.31	14605	1.20

(continued on next page)

1. INTRODUCTION

Helicopters have consistently exhibited relatively high unscheduled maintenance requirements because of the great percentage of high reliability risk and high-cost components needed for the helicopters unique performance capabilities. This tendency towards high maintenance requirements has generated concurrence among both the contractor and customer that improved reliability must be achieved without a long and expensive period of in-service product improvement. High initial reliability can be achieved only through a well-executed analytical design approach and an enthusiastic and well-controlled developmental testing effort.

The primary reliability effort in the design stage is the analysis and evaluation of the aircraft design and development of Reliability Predictions. Recent work has shown that a point estimate of aircraft or component reliability is meaningless unless accompanied by a quantification of the time in the components maturity (development) cycle for which the estimate is relevant.

Reliability growth prediction techniques have been employed to estimate the number of developmental test hours required to achieve a desired level of reliability with increased confidence in the technology.

However, since reliability continues to be improved by the Product Improvement process throughout most of the in-production life of a helicopter, it is necessary to understand this growth process. The magnitude and the factors affecting this growth process must be determined and quantified if future aircraft programs are to be optimized. Development costs and O&M costs must be viewed as intimately related to reliability. The key to minimum total system costs is the understanding of the reliability growth process through the development and operational phases.

Table 12 (continued)

INSTRUMENT, COMM AND NAV AIRCRAFT H-2(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	13103	4715	2.78	2043	6.41	18871	1.44
1969	3121	1261	2.48	511	6.11	4897	1.57
1970	8418	4420	1.90	1871	4.50	15930	1.89
1971	8412	4360	1.93	1885	4.46	16562	1.97
1972	10100	5286	1.91	2755	3.67	18540	1.84
1973	12185	4948	2.46	2534	4.81	16750	1.37

WEAPON SYSTEMS AIRCRAFT H-2(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	13103	54	242.65	24	545.96	275	.02
1969	3121	20	156.05	6	520.17	91	.03
1970	8418	47	179.11	20	420.90	80	.01
1971	8412	83	101.35	54	155.78	406	.05
1972	10100	212	47.64	110	91.82	612	.06
1973	12185	227	53.68	110	110.77	717	.06

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YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	13103	23458	.56	11994	1.09	105621	8.06
1969	3121	6392	.49	3018	1.03	29315	9.39
1970	8418	24123	.35	10897	.77	63117	7.50
1971	8412	22901	.37	11653	.72	69241	8.23
1972	10100	29199	.35	16282	.62	85850	8.50
1973	12185	29678	.41	16286	.75	94212	7.73

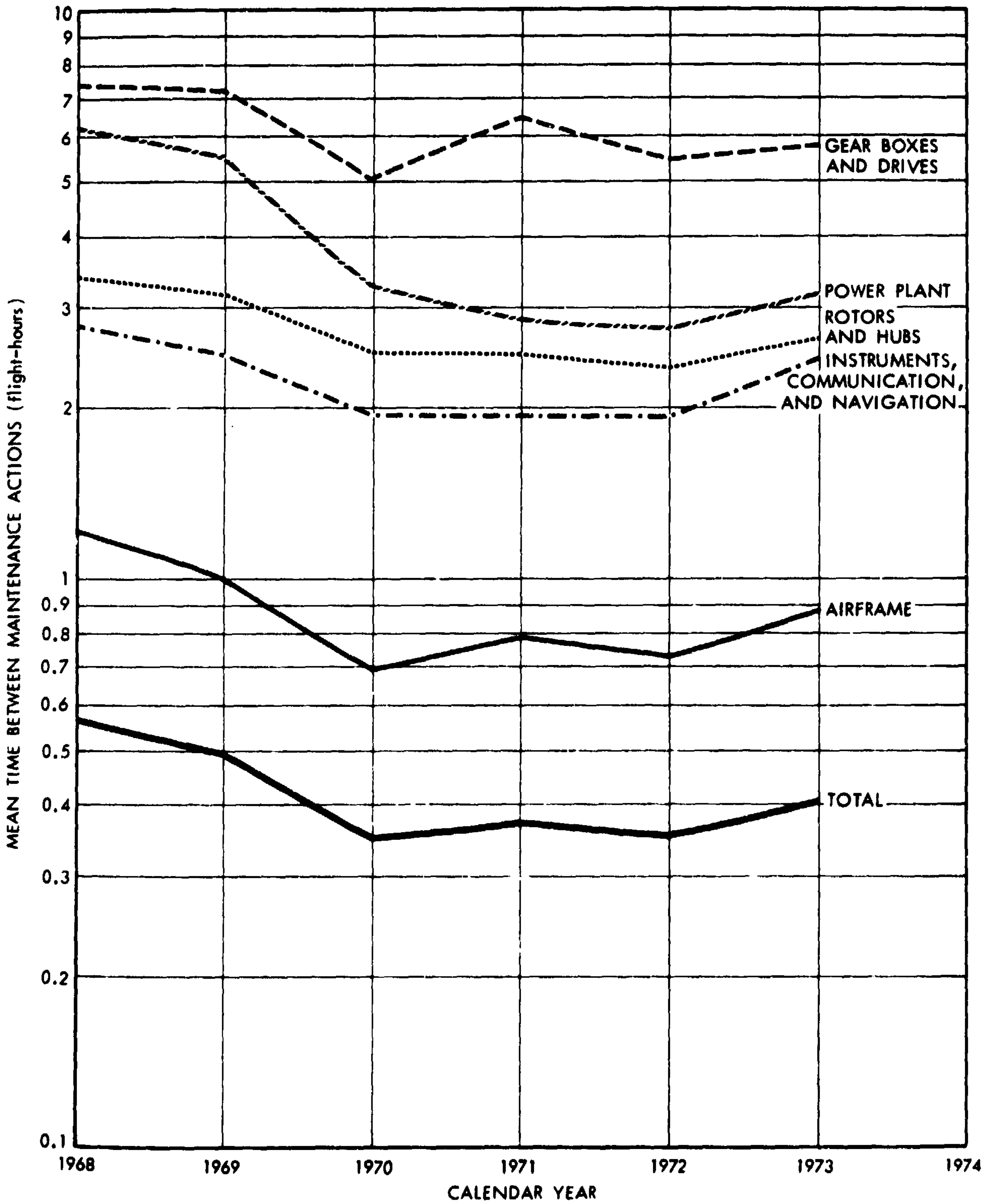

Figure 26. MTBMA FOR ALL NAVY H-2 MODELS

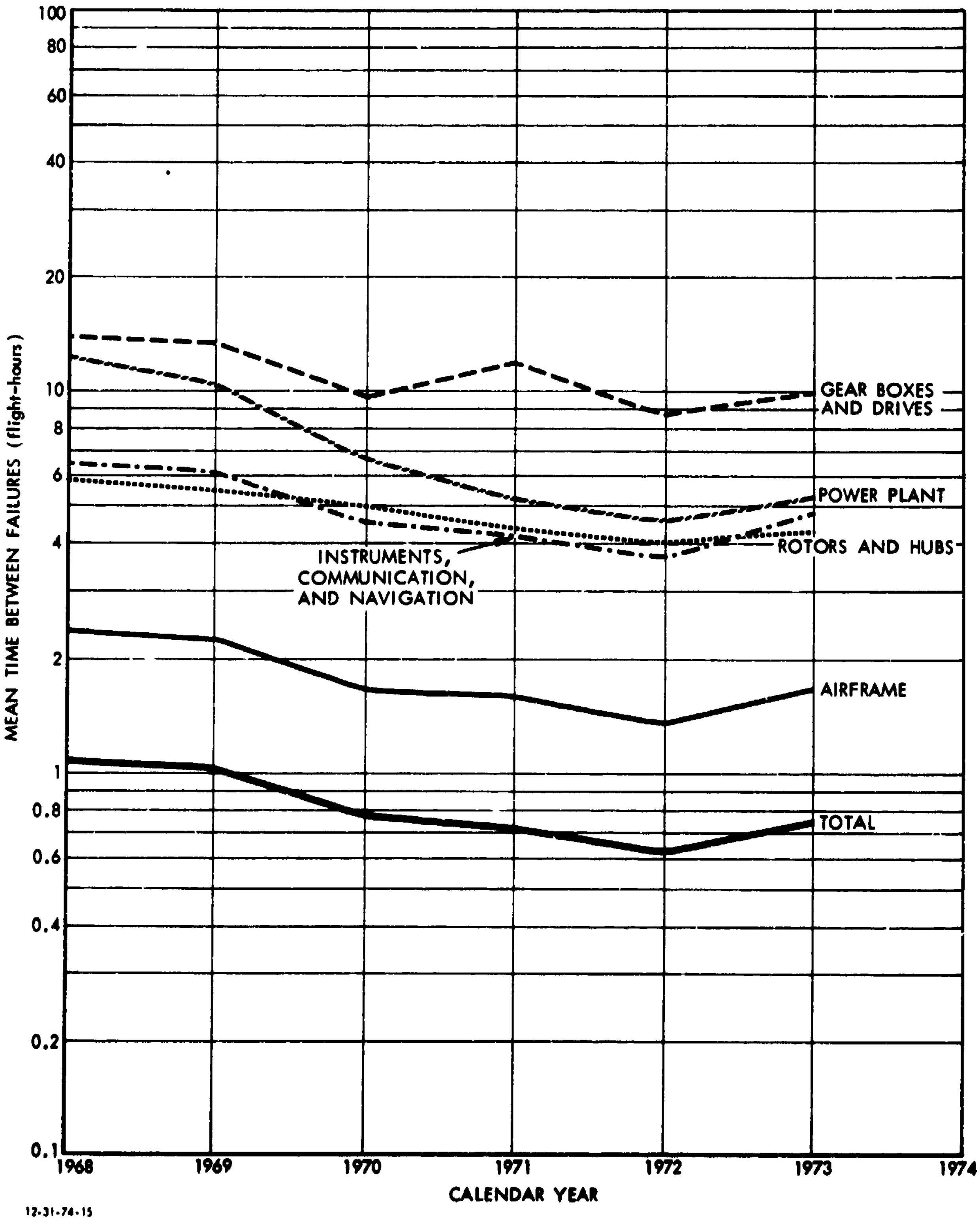

Figure 27. MTBF VERSUS YEAR FOR ALL NAVY H-2 MODELS

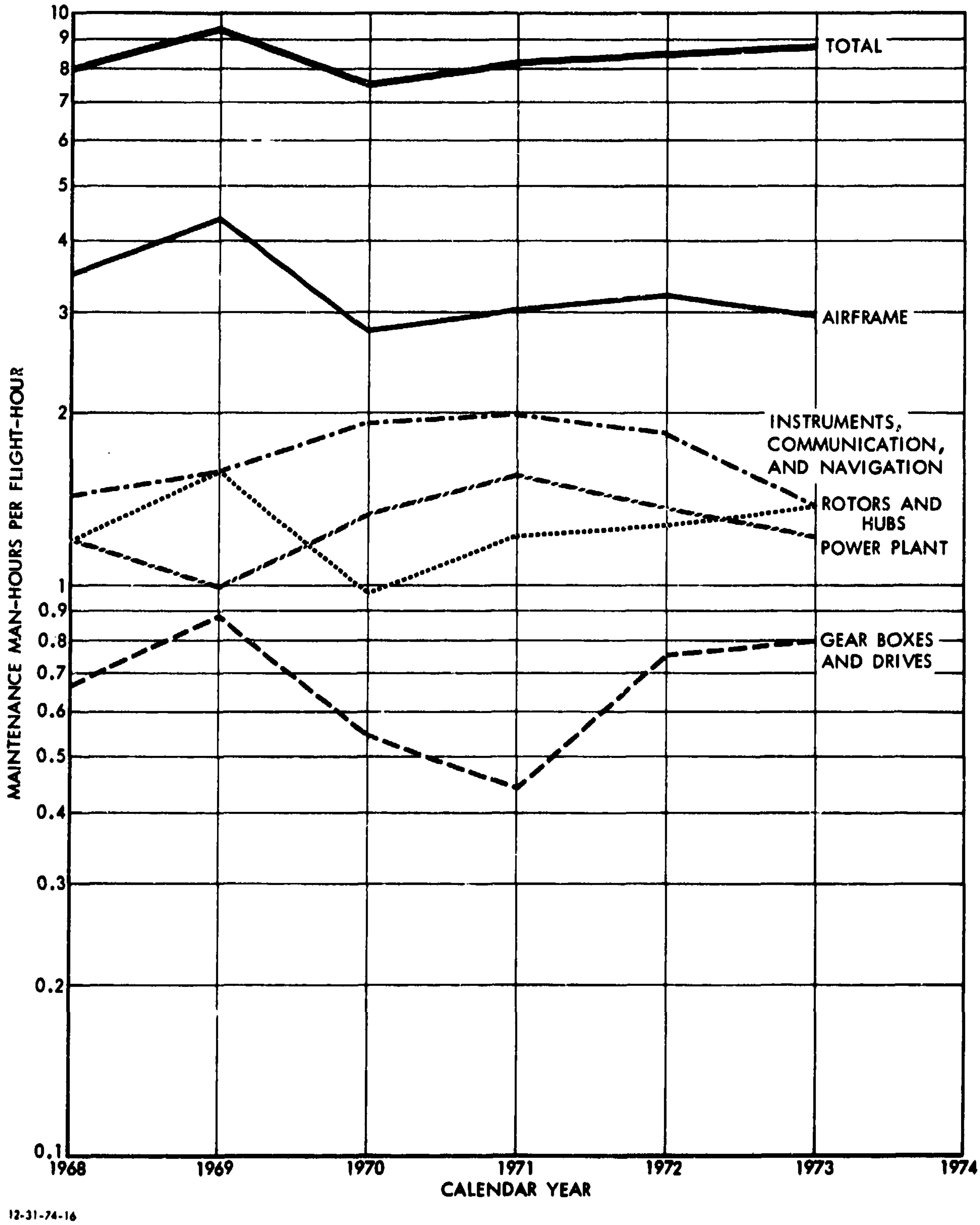

Figure 28. MMH/FH FOR ALL NAVY H-2 MODELS

3. The H-3

Most H-3 aircraft in Navy service are SH-3 aircraft (anti-submarine-warfare helicopters)--mainly SH-3A, SH-3G, SH-3D, and SH-3H aircraft. Table 13 presents 3-M data for all H-3 models; the three R/M measures are plotted in Figures 29-31. Relative to 1968, all three measures improved markedly in 1969; but after 1969 they worsened considerably, until they were worse in 1973 than they were in 1968. The trends for the various components do not appear to differ systematically from the trends for the total aircraft.

Table 13. NAVY 3-M DATA FOR ALL H-3 MODELS

AIRFRAME — AIRCRAFT H-3(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	40210	20991	1.92	11761	3.42	68341	1.70
1969	37835	13156	2.88	5960	6.35	41792	1.10
1970	29324	15225	1.93	8475	3.46	37073	1.26
1971	32838	24077	1.36	14102	2.33	59635	1.82
1972	36516	28906	1.26	17211	2.12	74414	2.04
1973	40909	34059	1.20	18884	2.17	88703	2.17

ROTORS AND HUBS(MAIN/TAIL) — AIRCRAFT H-3(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	40210	4280	9.39	2455	16.38	23165	.58
1969	37835	907	41.71	543	69.68	3957	.10
1970	29324	2822	10.39	1520	19.29	11150	.38
1971	32838	4613	7.12	2771	11.85	19981	.61
1972	36516	4894	7.46	2923	12.49	20986	.57
1973	40909	5915	6.92	3117	13.12	23605	.58

GEAR BOXES AND DRIVES — AIRCRAFT H-3(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	40210	1570	25.61	839	47.93	15044	.37
1969	37835	630	60.06	334	113.28	4024	.11
1970	29324	1257	23.33	687	42.68	7935	.27
1971	32838	2440	13.46	1513	21.70	17750	.54
1972	36516	2883	12.67	1700	21.48	17594	.48
1973	40409	3107	13.17	1709	23.94	18715	.46

POWER PLANT — AIRCRAFT H-3(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	40210	3446	11.67	1792	22.44	19408	.48
1969	37835	2477	15.27	1213	31.19	8779	.23
1970	29324	3530	8.31	1892	15.50	12067	.41
1971	32838	4839	6.79	2631	12.48	18143	.55
1972	36516	5094	7.17	2813	12.98	20329	.56
1973	40909	5944	6.88	3113	13.14	22931	.56

(continued on next page)

Table 13 (continued)

INSTRUMENT,COMM AND NAV — AIRCRAFT H-3(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	40210	13451	2.99	6707	6.00	58705	1.46
1969	37835	12189	3.10	3364	11.25	36012	.95
1970	29324	9210	3.18	3926	7.47	26944	.92
1971	32838	10500	3.13	4827	6.80	34512	1.05
1972	36516	12850	2.84	6518	5.60	47657	1.31
1973	40900	15437	2.65	7244	5.65	50632	1.24

WEAPON SYSTEMS — AIRCRAFT H-3(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	40210	511	78.69	154	261.10	1165	.03
1969	37835	615	61.52	111	340.86	1594	.04
1970	29324	648	45.25	232	126.40	1571	.05
1971	32838	754	43.55	295	111.32	1582	.05
1972	36516	1216	30.03	521	70.09	2943	.08
1973	40900	1586	25.79	658	62.17	3870	.09

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YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	40210	44249	.91	23708	1.70	186008	4.63
1969	37835	29474	1.28	11525	3.28	96148	2.54
1970	29324	32692	.90	16732	1.75	96740	3.30
1971	32838	47223	.70	26139	1.26	151603	4.62
1972	36516	55843	.65	31686	1.15	183923	5.04
1973	40900	66048	.62	34725	1.18	208546	5.10

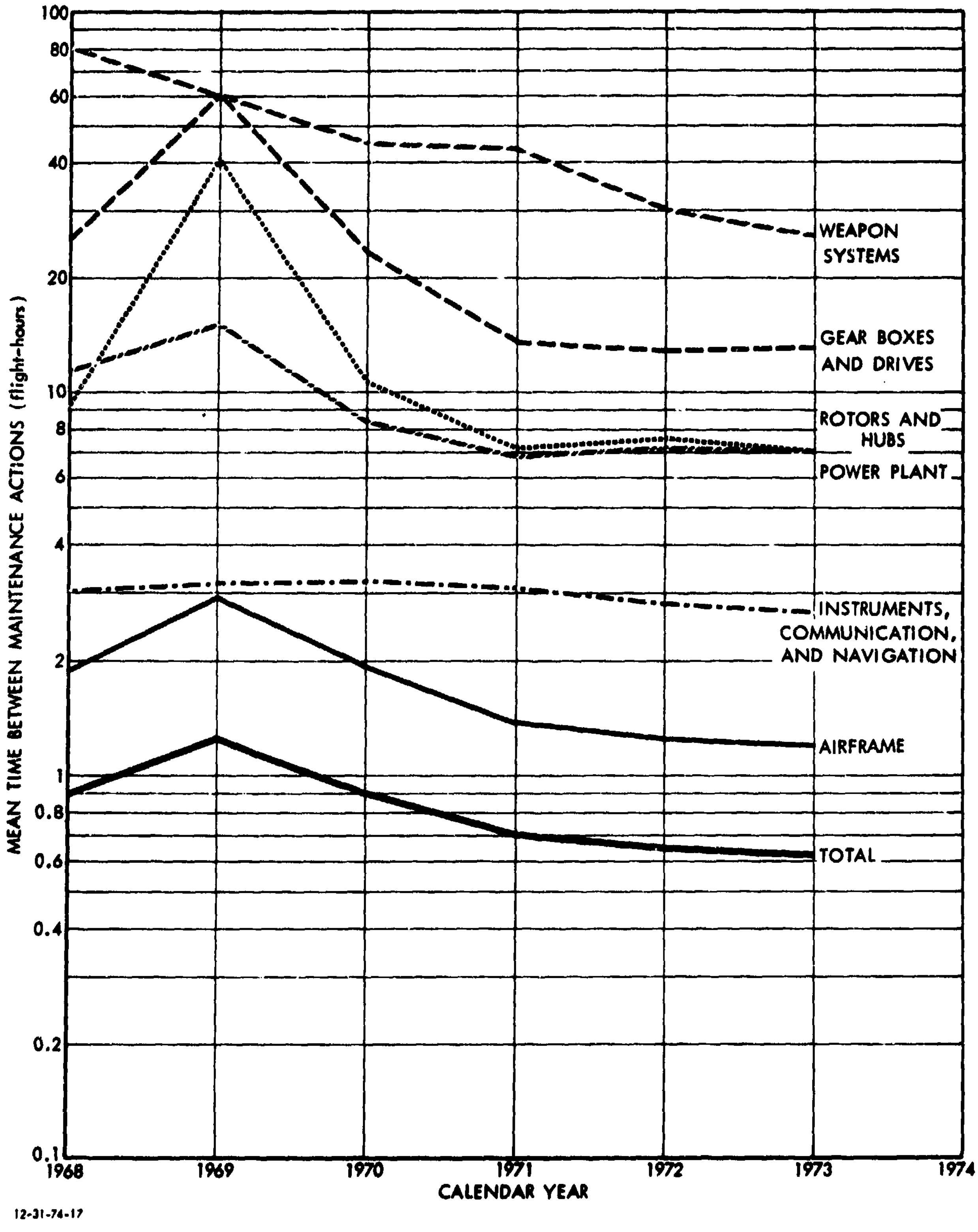

Figure 29. MTBMA FOR THE NAVY SH-3(S)

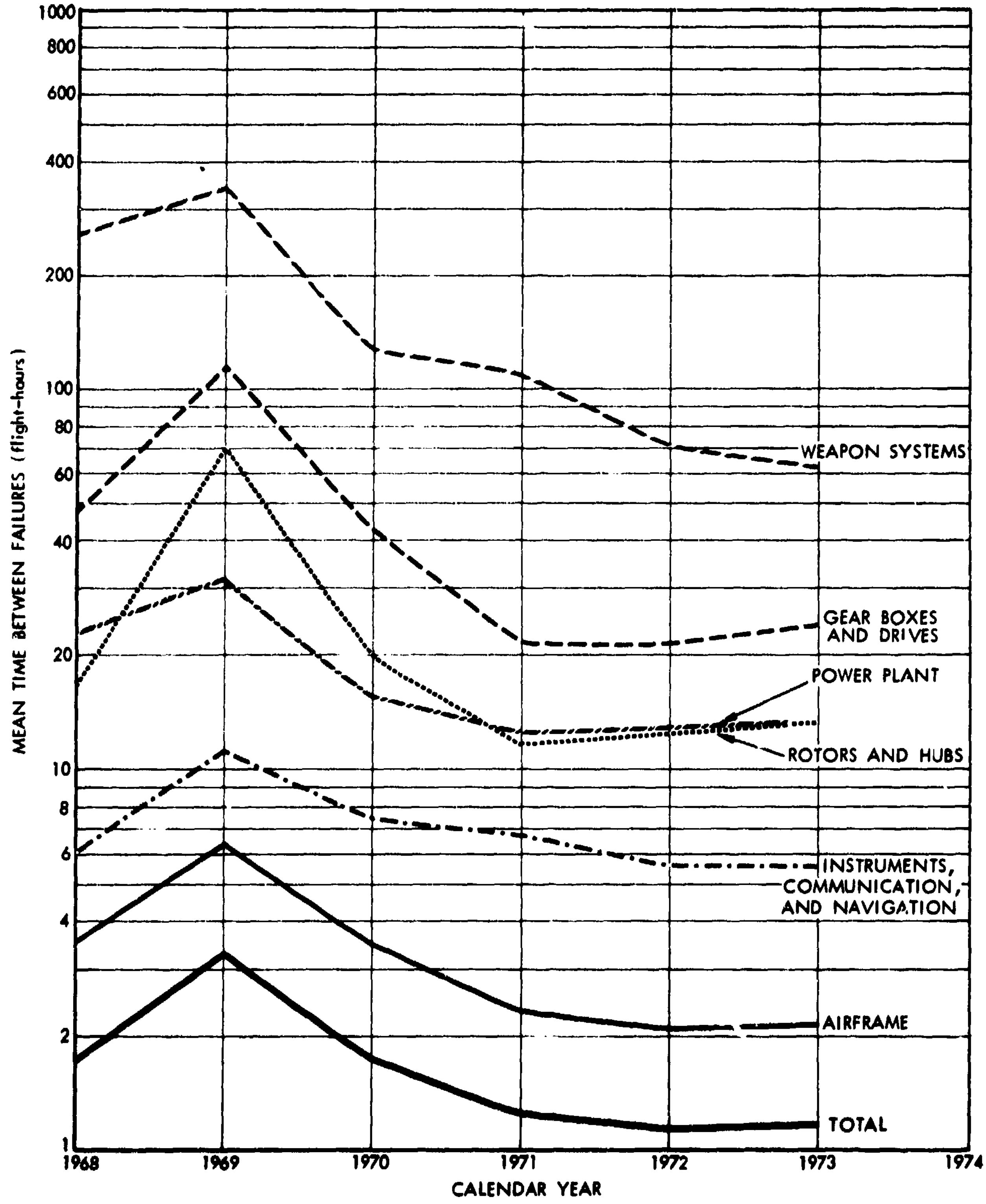

Figure 30. MTBF VERSUS YEAR FOR THE NAVY SH-3(S)

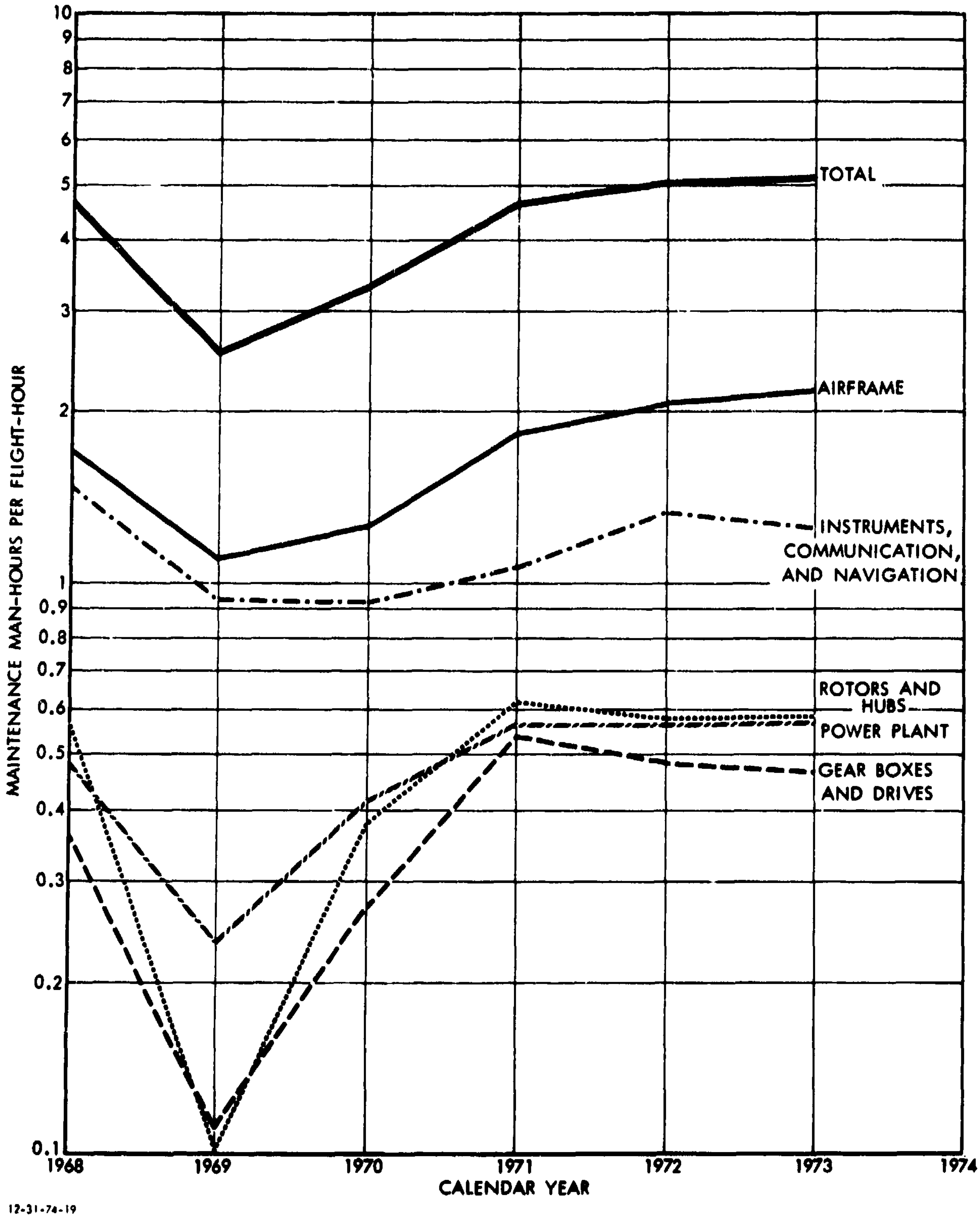

Figure 31. MMH/FH FOR THE NAVY SH-3(S)

4. The H-46

Most H-46 aircraft in Navy service are CH-46 aircraft (cargo helicopters)--mainly CH-46A, CH-46D, and CH-46F aircraft. Table 14 presents 3-M data for all H-46 models; the three R/M measures are plotted in Figures 32-34. The R/M measures show the same general pattern as those of the H-3 aircraft; relative to 1968, all three measures improved markedly in 1969; but after 1969 they worsened considerably, until they were worse in 1973 than they were in 1968. The trends for the various components do not appear to differ systematically from the trends for the total aircraft.

Table 14. NAVY 3-M DATA FOR ALL H-46 MODELS

AIRFRAME — AIRCRAFT H-46

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	26714	10958	2.44	6780	3.94	39111	1.46
1969	25079	8532	2.94	4582	5.47	29274	1.17
1970	32667	11952	2.73	7545	4.33	38758	1.19
1971	28820	13405	2.15	7974	3.61	44086	1.53
1972	27274	14684	1.86	8768	3.11	46349	1.70
1973	35857	23591	1.52	14468	2.48	86732	2.42

ROTORS AND HUBS(MAIN/TAIL) — AIRCRAFT H-46

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	26714	2576	10.37	1226	21.79	15361	.57
1969	25079	1668	15.04	688	36.45	7225	.29
1970	32667	2156	15.15	1316	24.82	11643	.36
1971	28820	2375	12.13	1394	20.67	11871	.41
1972	27274	3583	7.61	1861	14.66	14788	.54
1973	35857	6761	5.30	3412	10.51	37990	1.06

GEAR BOXES AND DRIVES — AIRCRAFT H-46

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	26714	1327	20.13	590	45.28	9161	.34
1969	25079	888	28.24	395	63.49	5707	.23
1970	32667	1406	23.23	828	39.45	8424	.26
1971	28820	1552	18.57	886	32.53	9451	.33
1972	27274	2036	13.40	1146	23.80	14697	.54
1973	35857	3003	11.94	1777	20.18	18093	.50

POWER PLANT — AIRCRAFT H-46

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	26714	1698	15.73	856	31.21	11775	.44
1969	25079	1196	20.97	494	50.77	5953	.24
1970	32667	2077	15.73	1145	28.53	12298	.38
1971	28820	2574	11.20	1381	20.87	16081	.56
1972	27274	2784	9.80	1529	17.84	16692	.61
1973	35857	4738	7.57	2524	14.21	26906	.75

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Table 14 (continued)

INSTRUMENT,COMM AND NAV AIRCRAFT H-46

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	26714	5663	4.72	3103	8.61	17629	.66
1969	25079	5074	4.94	1749	14.34	13712	.55
1970	32667	6589	4.96	3353	9.74	18703	.57
1971	28820	6414	4.49	3282	8.78	23568	.82
1972	27274	6915	3.94	3715	7.34	25416	.93
1973	35857	9993	3.59	5589	6.42	38134	1.06

WEAPON SYSTEMS AIRCRAFT H-46

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	26714	17	1571.41	6	4452.33	19	.00
1969	25079	47	533.60	7	3582.71	92	.00
1970	32667	213	153.37	88	371.22	623	.02
1971	28820	126	228.73	55	524.00	388	.01
1972	27274	188	145.07	84	324.69	645	.02
1973	35857	388	92.41	162	221.34	1567	.04

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YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	26714	22239	1.20	12561	2.13	92906	3.48
1969	25079	17405	1.44	7915	3.17	61963	2.47
1970	32667	24393	1.34	14275	2.29	90449	2.77
1971	28820	26446	1.09	14972	1.92	105445	3.66
1972	27274	30190	.90	17103	1.59	118587	4.35
1973	35857	48474	.74	27932	1.28	209422	5.84

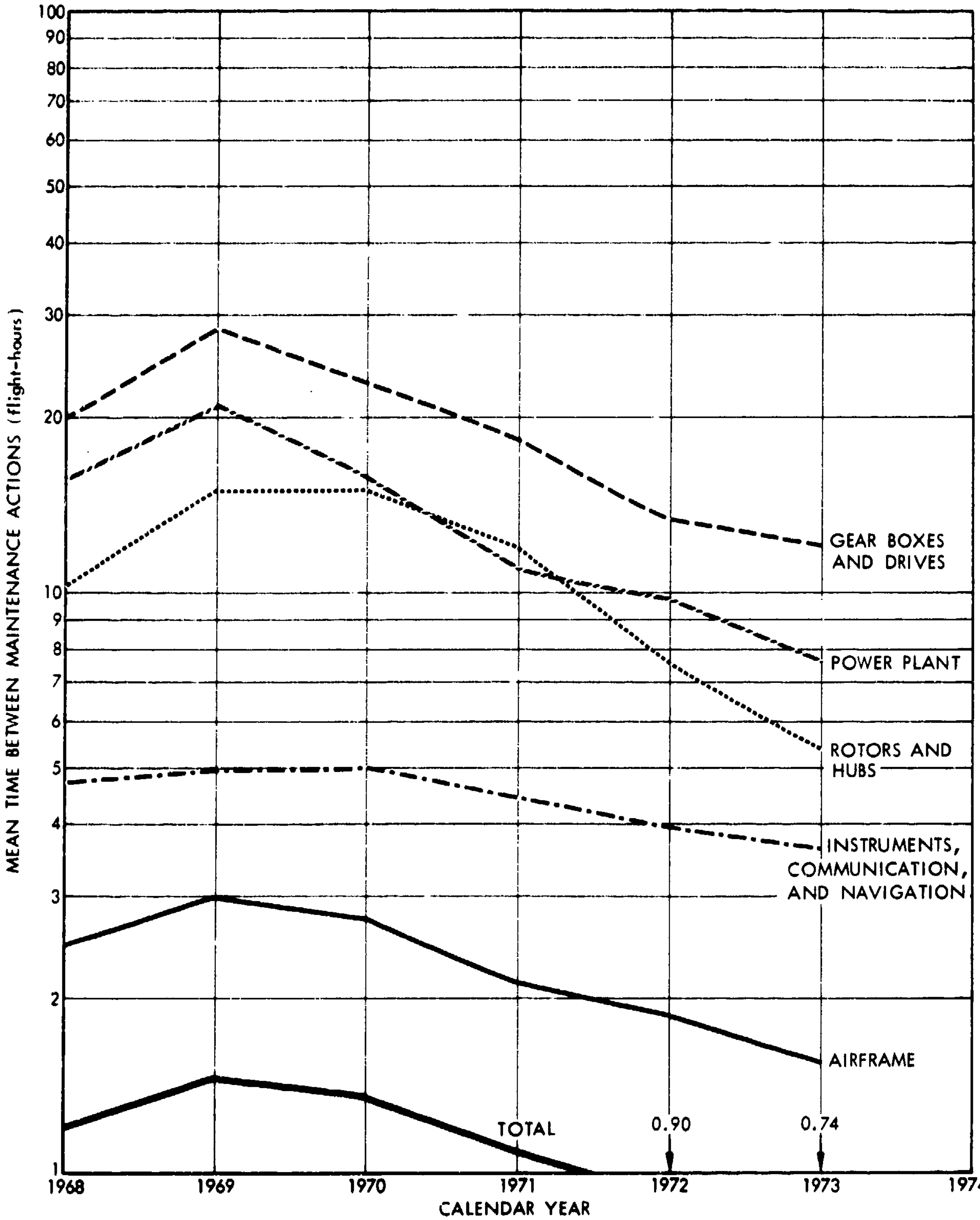

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Figure 32. M,EMA FOR THE NAVY H-46

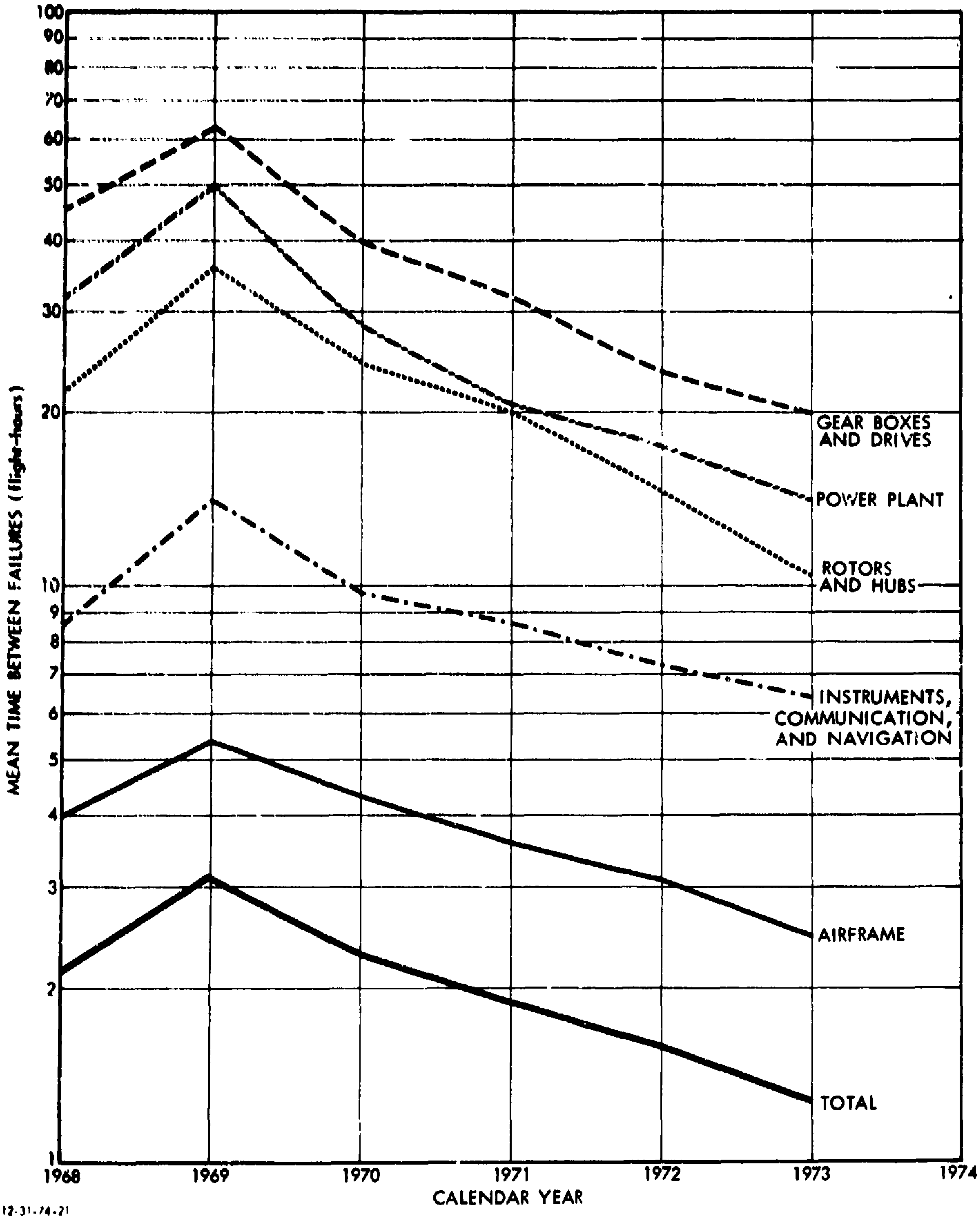

Figure 33. MTBF VERSUS YEAR FOR THE NAVY H-46

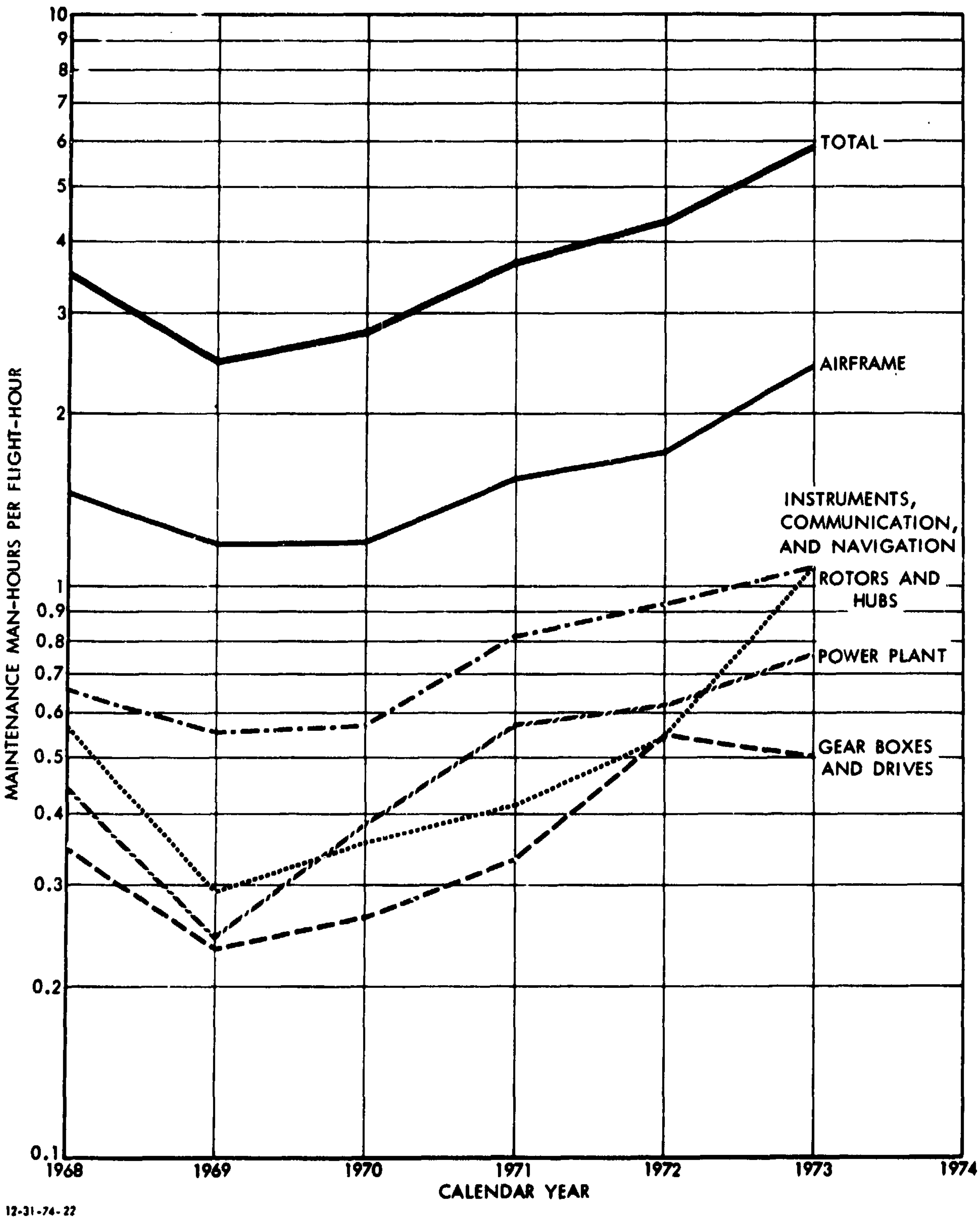

Figure 34. MMH/FH FOR THE NAVY H-46

5. The H-53

Most H-53 aircraft in Navy service are CH-53 aircraft (cargo helicopters)--mainly CH-53A and CH-53D aircraft. Table 15 presents 3-M data for all CH-53 models; the three R/M measures are plotted in Figures 35-37. Table 15 includes R/M measures for CH-53 weapon systems. However, since the weapon systems accounted for such a small portion of the total R/M activity, the weapon system data points in most cases did not fall on the R/M scales used in Figures 35-37 and therefore were not plotted on these figures. All three measures show a generally worsening trend over the 1968-73 period. There does not appear to be any systematic difference in the MTBMA and MTBF trends for the various components from the trends for the total aircraft. However, the MMH/FH trends indicate an improvement in power-plant MMH/FH, while the MMH/FH trends for the other components worsened.

Table 15. NAVY 3-M DATA FOR ALL H-53 MODELS

AIRFRAME — AIRCRAFT H-53(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	6209	3158	1.97	1856	3.35	14617	2.35
1969	5734	2958	1.94	1646	3.48	15342	2.68
1970	11378	5772	1.97	3728	3.05	24356	2.14
1971	12614	7275	1.73	4288	2.94	28821	2.28
1972	15126	11427	1.32	6812	2.22	40742	2.69
1973	18505	16814	1.10	10627	1.74	62851	3.40

ROTORS AND HUBS(MAIN/TAIL) — AIRCRAFT H-53(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	6209	576	10.78	339	18.32	4110	.66
1969	5734	406	14.12	195	29.41	4000	.70
1970	11378	1067	10.66	645	17.64	6641	.58
1971	12614	1439	8.77	860	14.67	9394	.74
1972	15126	2229	6.79	1317	11.49	12541	.83
1973	18505	3535	5.23	2179	8.49	24149	1.30

GEAR BOXES AND DRIVES — AIRCRAFT H-53(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	6209	500	12.42	233	26.65	3533	.57
1969	5734	397	14.44	187	30.66	2370	.41
1970	11378	984	11.56	661	17.21	5035	.44
1971	12614	1231	10.25	731	17.26	5344	.42
1972	15126	1888	8.01	1039	14.56	10664	.71
1973	18505	2648	6.99	1721	10.75	11295	.61

POWER PLANT — AIRCRAFT H-53(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	6209	754	8.23	469	13.24	6683	1.08
1969	5734	565	10.15	339	16.91	3342	.58
1970	11378	1088	10.46	740	15.38	3787	.33
1971	12614	1301	9.70	774	16.30	4563	.36
1972	15126	1774	8.53	1038	14.57	5834	.39
1973	18505	3295	5.62	1886	9.81	10506	.57

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Table 15 (continued)

INSTRUMENT,COMM AND NAV — AIRCRAFT H-53(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	6209	1366	4.55	613	10.13	4266	.69
1969	5734	1380	4.16	459	12.49	4727	.82
1970	11378	2663	4.27	1348	8.44	7620	.67
1971	12614	3496	3.61	1673	7.54	12708	1.01
1972	15126	4013	3.77	2069	7.31	14596	.96
1973	18505	5861	3.16	3353	5.52	22378	1.21

WEAPON SYSTEMS — AIRCRAFT H-53(S)

YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	6209	172	36.10	52	119.40	342	.06
1969	5734	166	34.54	35	163.83	351	.06
1970	11378	256	44.45	109	104.39	649	.06
1971	12614	279	45.21	132	95.56	692	.05
1972	15126	309	48.95	172	87.94	885	.06
1973	18505	385	48.06	195	100.03	871	.05

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YEAR	FLIGHT HRS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
1968	6209	6526	.95	3562	1.74	33551	5.40
1969	5734	5872	.98	2861	2.00	30132	5.25
1970	11379	11830	.96	7231	1.57	48088	4.23
1971	12614	15021	.84	8458	1.49	61522	4.88
1972	15126	21640	.70	12447	1.22	85262	5.64
1973	18505	32538	.57	19951	.93	132050	7.14

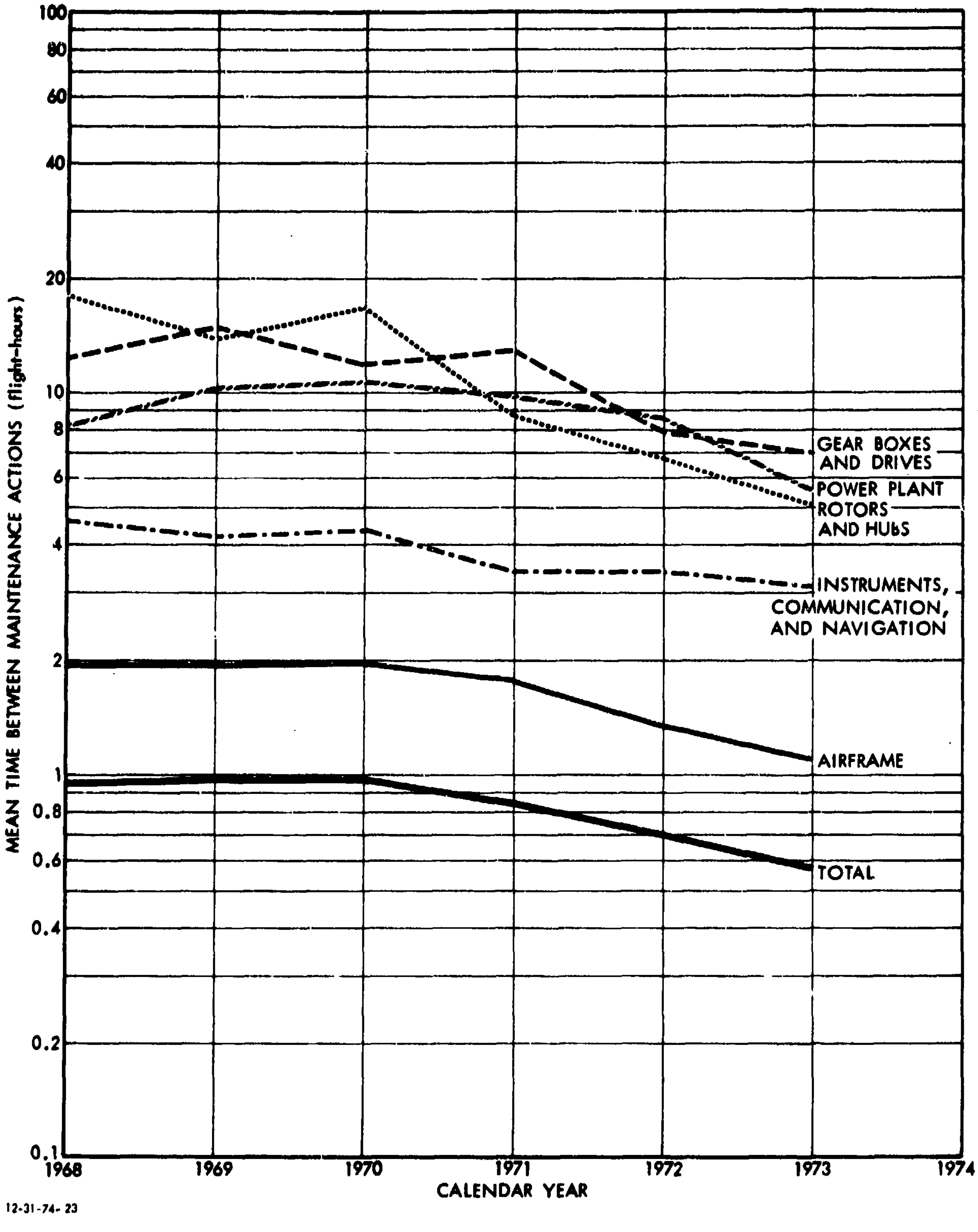

Figure 35. MTBMA FOR THE NAVY H-53(S)

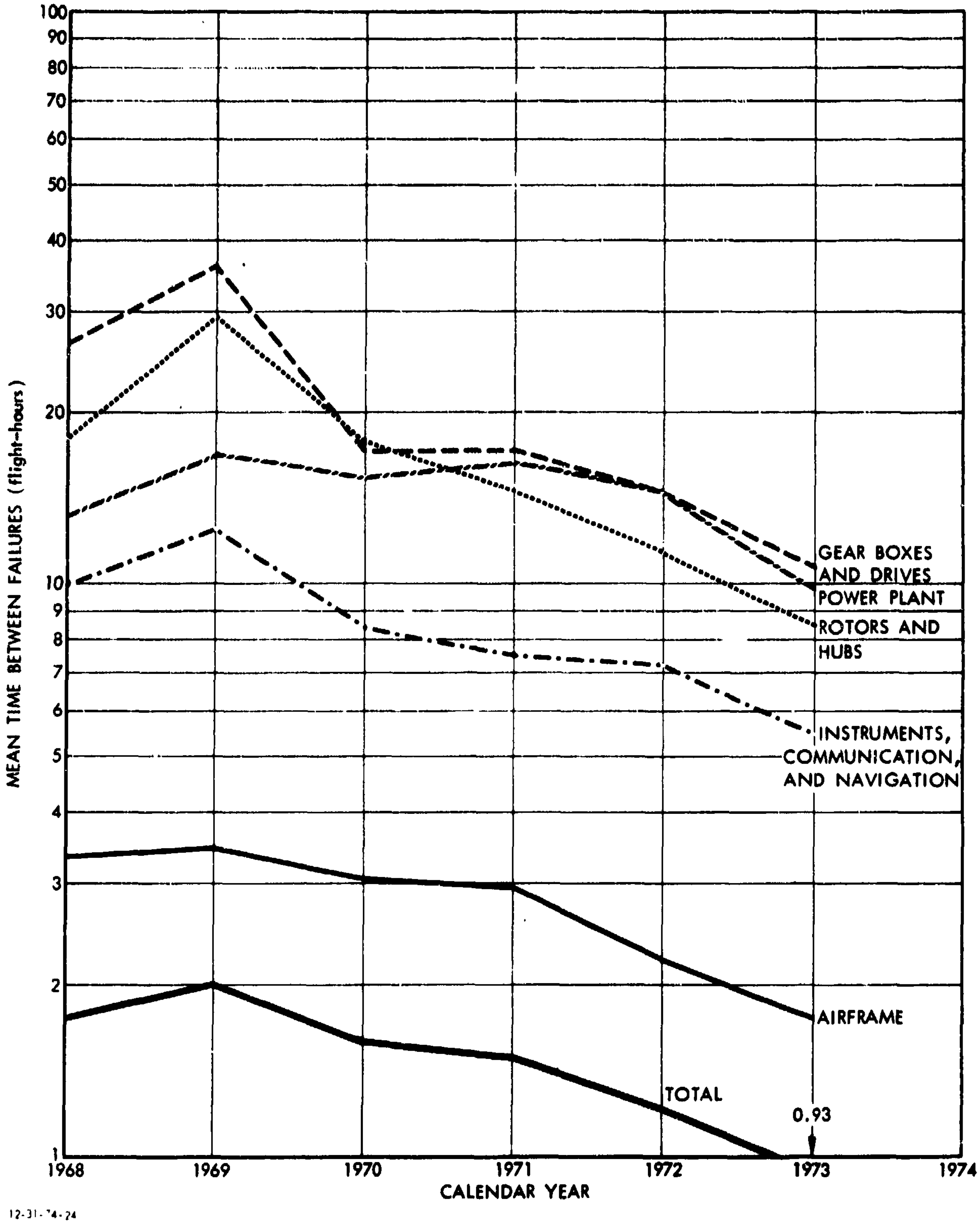

Figure 36. MTBF VERSUS YEAR FOR THE NAVY H-53(S)

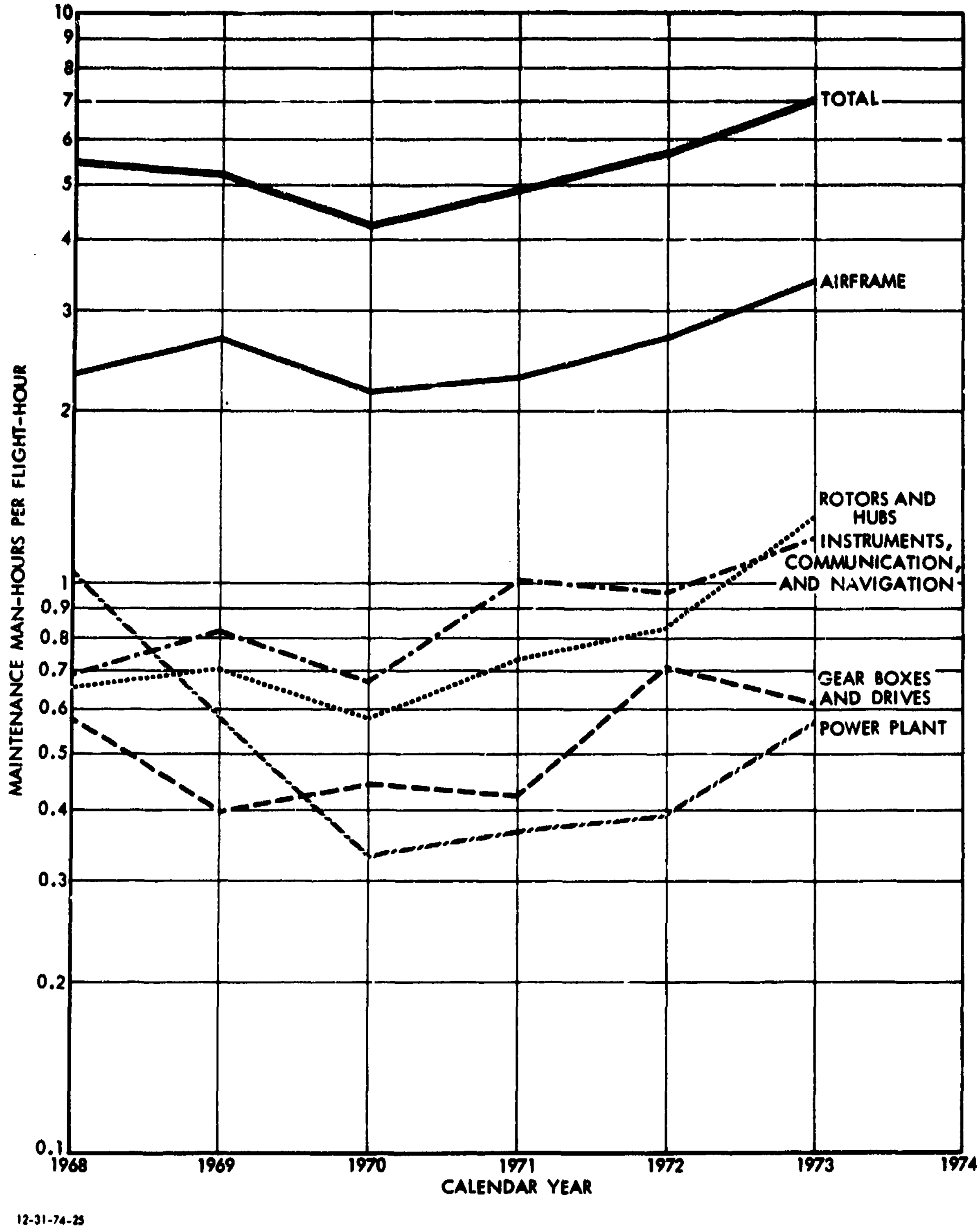

Figure 37. MMH/FH FOR THE NAVY H-53(S)

6. General Trends

The time trends of Figures 14-37 indicate that the R/M measures worsened over time in 21 of the 24 cases. In the other three cases,[1] the R/M measures remained approximately constant. Unfortunately, for all five basic types of helicopters the year of introduction into Navy inventory was before 1968. Hence, we cannot say definitely what the trend in R/M measures is from year of first introduction into service. However, mishap rates from the Naval Safety Center are available from time of introduction for all the Navy helicopters (see Table 17, in Ch. II, below). The Naval Safety Center data show a general worsening in mishap rates from time of introduction into the Navy inventory. Hence, it is probable that the three R/M measures worsen--or, at best, stay constant--from time of introduction into the inventory. Evidently, the aging of the fleet that occurs over time outweighs the beneficial effects of product improvements and results in an overall worsening of R/M measures during the service life of the aircraft.

C. AIR FORCE 66-1 DATA

Attempts at reading the AFM 66-1 data tapes containing failure, maintenance action, and man-hour counts covering Air Force helicopters were unsuccessful. The main obstacle encountered was getting a complete count of failures, maintenance actions, and expended man-hours from the tapes supplied us by the Air Force. For example, for the UH-1N aircraft our count of failures for the fourth quarter of 1973 (taken from the tapes) fell approximately 35 percent short of the count given in a sample of hard-copy output supplied by the Air Force. This hard-copy sample is a portion of the official report compiled and supplied to all commands by the Air Force Logistics Command,

[1]MTBMA and MMH/FH for the UH-1D/UH-1E/UH-1H/UH-1L/TH-1L/HH-1K models, and MMH/FH for the H-2.

Wright-Patterson AFB, Ohio. Although ACVMM is the group officially designated as responsible for preparing these reports, no long-term historical record of the data in reference is maintained--hence our requirement to read the original tapes.

According to the definition of a failure and the construction of the first tape record (which covers all work done "on" aircraft as opposed to work done on components removed from aircraft), the count of failures taken from the record should exceed the correct count. The downward adjustment indicated should come from "off" equipment records (shop work), wherein an item could be inspected and found not to be in a failed state--thus reducing the initial count of failures. Our attempt at reading this first record for the UH-1N (fourth quarter of 1973) produced the contrary result, an approximately 35-percent shortage of failures.

Consultation by telephone with Mr. Bill Harrison (ACVMM, Wright-Patterson AFB, Ohio), supplier of the tapes, confirmed that the definition we were using was correct and should have produced results corresponding to the sample copy. The difficulty appeared to flow from unidentifiable codes in the columns that are intended to indicate the type of aircraft to which a particular record entry applies. Mr. Harrison was not able to help in this matter. Accordingly, after expenditure of considerable time and effort, we decided that the remaining time for the study could be more fruitfully spent in other areas, and we abandoned the effort to obtain valid 66-1 data from the Air Force tapes.

Using maintenance data reported under the AFM 66-1 system, the Air Force publishes information on maintenance man-hour requirements for various types of equipment. Since these documents are reissued periodically, they should show trends in helicopter maintenance man-hours over calendar time. Table 16 presents Air Force MMH/FH for organizational and field maintenance. These figures reflect maintenance of the complete

aircraft (including communications, armament, and electronics equipment). The basic helicopter types shown in the table may include several different models; for example, the Air Force has procured several different models of the H-1 series. Table 16 includes all revisions of these data published from October 1955 through August 1974.

Table 16. AIR FORCE MMH/FH FOR ORGANIZATIONAL AND FIELD MAINTENANCE

Heli-copter Type	Oct. 1955	Dec. 1956	Sep. 1962	Jan. 1963	Oct. 1965	Oct. 1966	Mar. 1967	May 1969	Feb. 1973
H-18	11.7	--	--	--	--	--	--	--	--
H-5	7.9	8.6	--	--	--	--	--	--	--
H-23	13.3	14.5	--	--	--	--	--	--	--
H-13	11.6	12.6	6.3	6.3	5	5	5	5	--
H-19	11.6	20.7	11.5	11.5	13	13	13	13	--
H-21	13.2	24.5	16.8	16.8	14	17	17	21	21
H-43	--	--	14.7	14.7	13	13	13	10	12
H-1	--	--	--	10.0	8	10	8	10	10
H-3	--	--	--	20.3	15	17	17	17	22
H-34	--	--	--	--	14	14	14	14	21
H-53	--	--	--	--	--	--	17	17	22
H-47	--	--	--	--	--	--	17	--	10

Source: 1955-63: Reference [13].
1965-73: Reference [14].

The September 1962 and January 1963 publications gave two sets of figures for the H-19 and H-21: one for monthly flight-hours (for the detachment) less than 300 and one for monthly flight-hours greater than 300. In each of those four cases, averages of the two figures are presented in Table 16. Three types (H-13, H-43, and H-47) show improvement in MMH/FH over time; seven types (H-5, H-23, H-19, H-21, H-3, H-34, and H-53)

show a worsening (increase in MMH/FH), and one type (H-1) was essentially constant. Hence these data indicate that, in general, MMH/FH tend to worsen over time.

Chapter II

SERVICE MISHAP RATES

All three Services maintain reporting systems for aircraft "mishaps." These reporting systems are all similar in concept but differ in detail among the Services. There are different categories of mishaps, but in general they cover all incidents of a dangerous or potentially dangerous character--from minor incidents (such as precautionary landings) through major accidents, in which the aircraft is heavily damaged or lost. The cause of the accident is also reported; there are a number of cause categories, and more than one may be involved in a single mishap. For example, if a transmission warning-light indicates an incipient transmission failure and the pilot damages the landing gear in making an emergency landing, that mishap may show both "Materiel Failure" and "Pilot Error" as having contributed to the accident.

A. REPORTING SYSTEMS AND AVAILABLE DATA

Each Service's reporting system and available data are discussed separately below.

1. Army

The Army mishap data is reported by the U.S. Army Agency for Aviation Safety (USAAAVS), Fort Rucker, Alabama. The reporting starts with the introduction of the aircraft into regular service use; the test period prior to service use is not covered. In addition to the Mishap Summary, USAAAVS publishes "Flight Fax," which reports all accidents and precautionary landings. However,

the data making up "Flight Fax" must be reported electronically to USAAAVS within eight hours of the occurrence. For this reason, USAAAVS personnel felt that the Mishap Summary was more reliable and would be best for our purposes.

In the Army reporting system, mishaps are categorized as total losses, major accidents, minor accidents, incidents, forced landings, and precautionary landings. The difference between major and minor accidents and between minor accidents and incidents is established for each aircraft type by the number of man-hours required to repair.

The Army reporting system includes the following summary "Cause Factors":

- Personnel
  - Flight Crew
  - Ground Crew
  - Supervisory
- Environmental
  - Facilities
  - Command
  - Training
- Materiel[1]
  - Failure/Malfunction
  - Maintenance
  - Design
- Weather.

As already noted, it is possible that a single mishap may involve more than one cause factor--which is true even within the major cause-factor categories. For example, a mishap involving materiel may be charged to more than one of the three subfactors under materiel.

For each helicopter type, we received mishap data from USAAAVS for the active Army worldwide inventory; these data exclude mishaps caused by combat. The Army indicated that its

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[1]The Army and Air Force use this spelling; the Navy uses "Material." In this report we use "Materiel" throughout.

TABLE 2 - CH-47 SYSTEM REM GROWTH parameters

SYSTEM	MMH/FH - CUM*			MAL/FH - CUM		
	β	α	R	β	α	R
AIRFRAME	1.997	-.152	-.957	-1.915	.060	.704
POWER PLANT	-.127	-.017	-.157	-.766	-.048	-.539
FLIGHT CONTROL	2.631	-.295	-.971	2.010	-.315	-.965
ROTOR	-.774	-.005	-.088	-.957	-.120	-.897
INDICATING	.186	-.197	-.849	-1.619	-.073	-.849
EQUIPMENT	3.475	-.415	-.970	-.773	-.159	-.959
COMM/NAV	.883	-.268	-.931	-.068	-.224	-.907
HYDRAULIC	-.236	-.195	-.864	-1.456	-.142	-.958
LANDING GEAR	.101	-.220	-.972	-1.794	-.133	-.870
DRIVE	2.336	-.219	-.948	-3.939	.160	.951
ELECTRICAL	-.018	-.212	-.950	-.926	-.147	-.821
TOTAL	3.510	-.172	.934	1.044	-.063	-.884

* - ORGANIZATIONAL + Integrated Direct support, Direct maintenance manhours.

$\sigma_y = \sqrt{\frac{\sum_{i=1}^{m} (\ln x_i - \bar{X})^2}{m}}$

ASSUMED RELATIONSHIP

$\ln Y = \alpha \ln X + \beta$

ie $Y = e^{\beta} X^{\alpha}$

where

Y = cum malfunctions/flight hour
or Y = cum maintenance manhours/flight hour

and
X = cum flight hours

also

R = Correlation co-efficient

$\bar{X} = \frac{\ln \sum_{i=1}^{m} x_i}{m} = \sqrt[m]{\prod_{i=1}^{m} x_i}$

$\bar{Y} = \sqrt[m]{\prod_{i=1}^{m} y_i}$

$\sigma_x = \sqrt{\frac{\sum_{i=1}^{m} (\ln x_i - \bar{x})^2}{m}}$

mishap data before FY 1968 were less reliable and advised against our using them. Accordingly, the data reported herein cover the six FYs 1968-73. For each helicopter type, we assembled the following data by fiscal year:

- Number of flight-hours
- Number of accidents (total of total losses--both major and minor accidents):
  - Materiel failure
  - Total.
- Number of mishaps (total of three accident types: incidents, forced landings, and precautionary landings):
  - Materiel failure
  - Total.

Using these data, we calculated mishap rates per 10,000 flight-hours (Table 17) and plotted the four mishap rates versus fiscal year (Figure 38a-g). In some cases when a helicopter was entering or being phased out of service and the mishap rates were not meaningful, the data for those years were not included in our tables or figures.

Mishap rates involving materiel were shown, because they should reflect reliability growth, if any, in the helicopter fleet being achieved through design or process improvement. The mishap rates were plotted on semi-log paper, so that equal rates of change would be parallel at any location on the paper.[1] For both accident rates and total mishap rates, the change in rates involving materiel generally followed the total rates. In most cases, surprisingly, the rates for all mishaps tended to increase over time, while the accident rates either decreased or remained approximately constant over time. In discussing these results, USAAVS personnel offered the following probable reasons for these two trends.

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[1]Since log paper does not go to 0.0, a zero accident rate (whenever it occurred) was plotted at the bottom of the mishap-rate scale.

Table 17. MISHAPS OF ARMY HELICOPTERS

Helicopter Series	FY	Number: Accidents: Materiel Failure	Number: Accidents: Total	Number: Mishaps: Materiel Failure	Number: Mishaps: Total	Flight-Hours	Rate (per 10,000 flight-hours): Accidents: Materiel Failure	Rate: Accidents: Total	Rate: Mishaps: Materiel Failure	Rate: Mishaps: Total
UH-1	68	188	550	1,147	1,919	2,224,702	0.8	2.5	5.2	8.6
	69	232	544	1,950	3,230	2,564,718	0.9	2.1	7.6	12.6
	70	212	481	2,169	3,026	2,687,434	0.8	1.8	8.1	11.3
	71	149	299	1,466	2,397	2,122,168	0.7	1.4	6.9	11.3
	72	38	136	1,176	1,590	1,266,471	0.3	1.1	9.3	12.6
	73	14	37	756	982	786,840	0.2	0.5	9.6	12.5
AH-1	68	5	15	37	69	44,085	1.1	3.4	8.4	15.6
	69	35	92	187	342	270,764	1.3	3.4	6.9	12.6
	70	66	110	401	523	399,870	1.7	2.8	10.0	13.1
	71	46	74	334	527	303,122	1.5	2.4	11.0	17.4
	72	17	39	309	361	179,260	0.9	2.2	17.2	20.1
	73	8	22	153	222	87,814	0.9	2.5	17.4	25.3
OH-6	68	22	60	76	139	77,426	2.8	7.8	9.8	18.0
	69	76	206	223	513	413,393	1.8	5.0	5.4	12.4
	70	85	193	242	480	454,460	1.9	4.2	5.3	10.6
	71	41	103	191	420	287,935	1.4	3.6	6.6	14.6
	72	17	48	108	192	130,303	1.3	3.7	8.3	14.7
	73	9	12	17	40	25,794	3.5	4.7	6.6	15.5
CH-37	68	0	1	25	29	5,961	0.0	1.7	41.7	48.3
	69	3	3	25	26	5,315	5.7	5.7	47.2	49.1
	70	0	0	10	11	2,485	0.0	0.0	40.0	44.0
	71	0	0	2	2	352	0.0	0.0	50.0	50.0
	72	--	--	--	--	--	--	--	--	--
	73	--	--	--	--	--	--	--	--	--

(continued on next page)

Table 17 (continued)

Heli-copter Series	FY	Number				Flight-Hours	Rate (per 10,000 flight-hour)			
		Accidents		Mishaps			Accidents		Mishaps	
		Materiel Failure	Total	Materiel Failure	Total		Materiel Failure	Total	Materiel Failure	Total
CH-47	68	7	21	166	219	195,962	0.4	1.1	8.5	11.2
	69	16	33	254	331	241,906	0.7	1.4	10.5	13.7
	70	16	31	276	341	261,262	0.6	1.2	10.5	13.0
	71	16	21	281	403	196,124	0.8	1.1	14.3	20.6
	72	9	8	192	224	112,760	0.8	0.7	17.0	19.9
	73	1	2	114	137	52,718	0.2	0.4	21.7	26.0
CH-54	68	1	2	15	18	8,826	1.1	2.3	17.0	20.5
	69	2	3	13	22	19,080	1.0	1.6	6.8	11.5
	70	1	2	36	35	23,044	0.4	0.9	15.7	15.2
	71	3	2	18	26	13,363	2.2	1.5	13.4	19.4
	72	0	2	15	20	9,791	0.0	2.0	15.3	20.4
	73	0	1	19	27	7,214	0.0	1.4	26.4	37.5
OH-58	68	--	--	--	--	--	--	--	--	--
	69	0	0	0	0	112	0.0	0.0	0.0	0.0
	70	3	6	40	62	76,462	0.4	0.8	5.2	8.1
	71	14	46	126	258	262,645	0.5	1.8	4.8	9.8
	72	17	38	230	356	279,055	0.6	1.4	8.2	12.8
	73	10	24	229	376	275,021	0.4	0.9	8.3	13.7

Source: U.S. Army Agency for Aviation Safety, Ft. Rucker, Alabama.

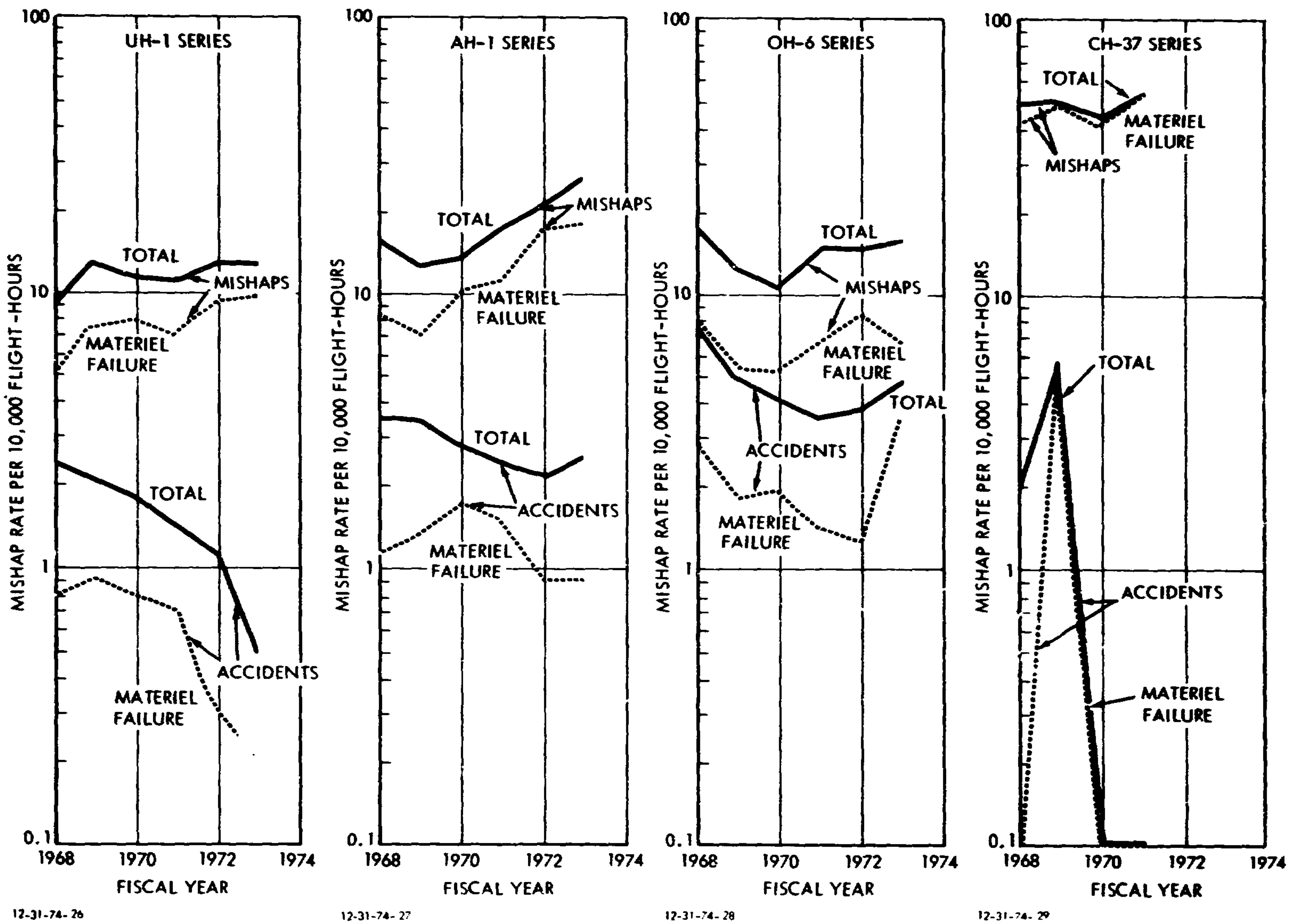

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Figure 38. MISHAP RATES FOR ARMY HELICOPTERS

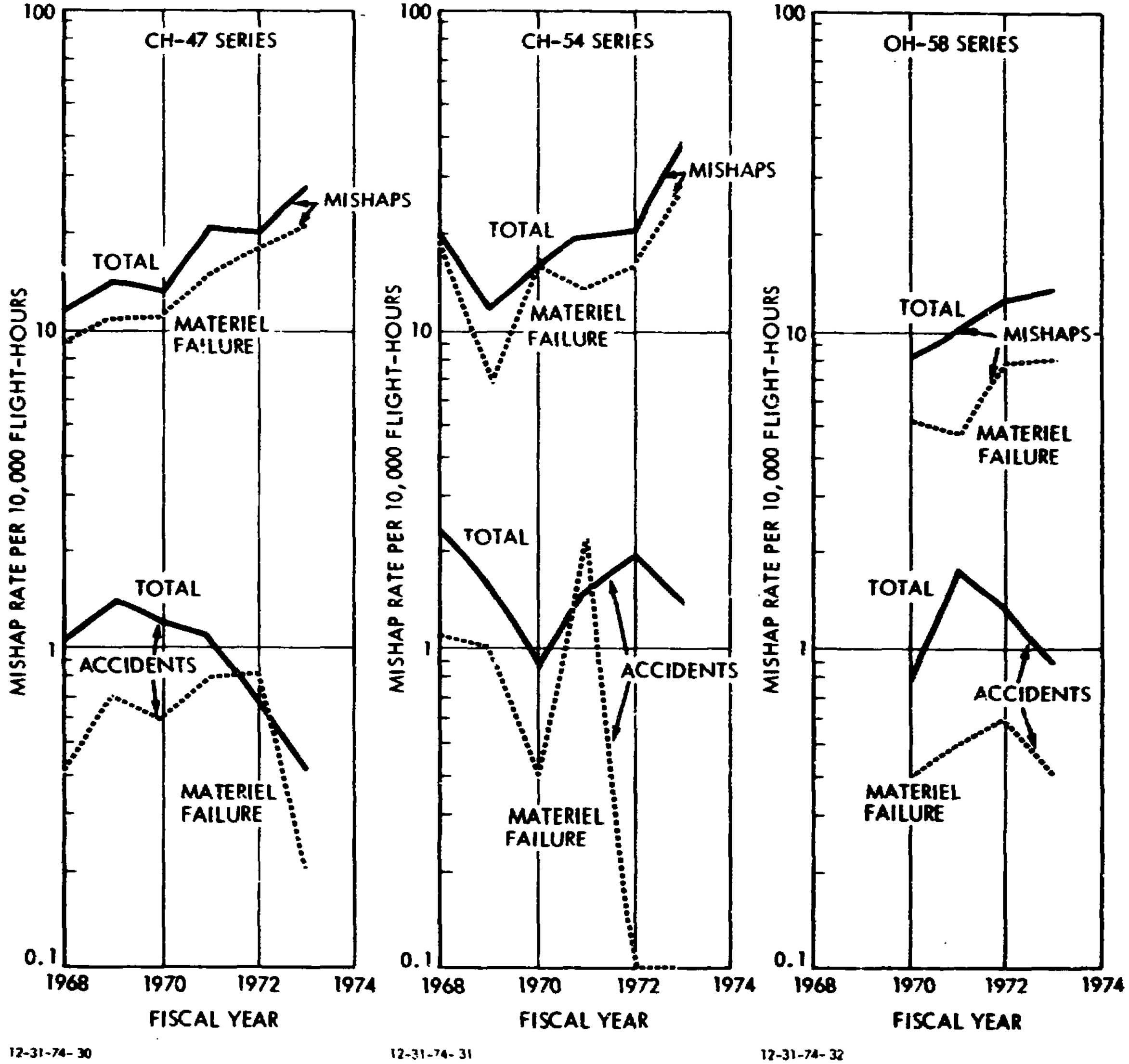

Figure 38 (continued)

(1) Serious problems causing accidents tend to be corrected first (thus reducing the accident rate), while minor problems receive less attention.

(2) With the deceleration of the Vietnam conflict, less mission pressure encouraged pilots to make precautionary landings in order to reduce the possibility of accidents.

(3) Though the development of better fault-warning systems has increased precautionary landings and other incidents, it has reduced accidents.

(4) Progressively more mishaps occur as the fleet ages, much as is the case with old automobiles.

Hence, though there appears to be either approximately constant or increasing reliability insofar as accidents are concerned, there appears to be a deterioration in reliability insofar as all mishaps (both those involving materiel and total) are concerned.

2. Navy

Navy mishap data are reported by the Naval Safety Center (NSC), Norfolk, Virginia. The reporting starts with the testing of the aircraft at the Naval Air Test Center, Patuxent River. However, the data we obtained for helicopters during this period appeared unreliable, and only data for regular Service use appeared usable for our purposes. In the Navy reporting systems, mishaps are broken down as follows:

Major Accident	- Involves loss or substantial damage to aircraft.
Minor Accident	- Minor or limited damage.
Incident	- Very minor damage or no damage (e.g., an engine failure followed by a successful autorotative landing, or an abort following main engine start).
Ground Accident	- No intent to fly (includes injuries to maintenance personnel during maintenance).

The difference between major and minor accidents is established for each aircraft type by the number of man-hours required to

repair; heavy damage to a major component (which may not take many man-hours to replace is also considered as a major accident.

The Navy reporting system includes the following "Contributing Causes":

Pilot

Other Personnel

Materiel
- Failure or Malfunction
- Design
- Maintenance-Personnel-Induced
- Pilot-Induced

Weather

Airport Facility

Carrier/LPH Facility.

There are a number of other contributing causes, in addition to those listed above. However, the great majority of mishaps involve the first three categories above (including the subcategories under "Materiel"). As with the Army, it is possible that a single mishap may involve more than one cause.

For each helicopter type now in Navy service, we received mishap data from the fiscal year of introduction into service through FY 1973 for the Navy worldwide inventory; the Navy excluded mishaps caused by combat in these data. For each helicopter type, we assembled the following data by fiscal year:

- Number of flight-hours.
- Number of major accidents:
  - Involving pilot error
  - Involving other personnel error
  - Involving materiel failure
  - Total.
- Number of minor accidents or incidents:
  - Involving pilot error
  - Involving other personnel error
  - Involving materiel failure
  - Total.

- Ground Accidents:
  - Involving pilot error
  - Involving other personnel error
  - Involving materiel failure
  - Total.
- Total mishaps:
  - Involving pilot error
  - Involving other personnel error
  - Involving materiel failure
  - Total.

Although the present Navy system reports minor accidents separately from incidents, prior to FY 1968 the two were reported as a single category. For this reason, in order to have a consistent time series we have combined them, since all Navy helicopter types presently in service were in the inventory before FY 1968. Using these data, we calculated mishap rates per 10,000 flight-hours (Table 18). In general, there are somewhat fewer major accidents than ground accidents, while the great majority of mishaps involve minor accidents or incidents. However, even though major accidents account for the fewest mishaps of the three categories, they are probably the most important in terms of total cost (both in materiel loss and in injuries and fatalities). Major accident rates (involving materiel and total) and all mishaps (involving materiel and total) were plotted versus fiscal year (Figures 39a-e). In some cases when a helicopter was entering service and the mishap rates were not meaningful, the data for those years were not included in our tables or figures.

The general pattern of the Navy mishap rates is similar to that for the Army. In general, the accident rates either decreased or remained approximately constant over time while the total mishap rates increased. Personnel at NSC felt that the quality and attitude of maintenance personnel were also factors in the worsening mishap rate. They indicated that (1) the better maintenance personnel are assigned to the newer aircraft types

Table 18. MISHAPS OF NAVY HELICOPTERS

Helicopter Series	FY	Mishap Type*	Number				Flight-Hours	Rate (per 10,000 flight-hours)			
			Pilot Error	Other Personnel Error	Materiel Failure	Total		Pilot Error	Other Personnel Error	Materiel Failure	Total
H-1	65	Major	1	1	1	2	17,125	0.6	0.6	0.6	1.2
		Minor	4	5	0	6		2.3	2.9	--	3.5
		Ground	0	2	0	2		--	1.2	--	1.2
		Total	*5*	*8*	*1*	*10*		*2.9*	*4.7*	*0.6*	*5.8*
	66	Major	0	2	1	5	38,443	--	0.5	0.3	1.3
		Minor	8	7	10	25		2.1	1.8	2.6	6.5
		Ground	0	4	0	4		--	1.0	--	1.0
		Total	*8*	*13*	*11*	*34*		*2.1*	*3.4*	*2.9*	*8.8*
	67	Major	7	4	3	15	55,755	1.3	0.7	0.5	2.7
		Minor	13	4	19	40		2.3	0.7	3.4	7.2
		Ground	0	4	0	4		--	0.7	--	0.7
		Total	*20*	*12*	*22*	*59*		*3.6*	*2.2*	*3.9*	*10.6*
	68	Major	11	10	10	25	70,237	1.6	1.4	1.4	3.6
		Minor	22	22	52	93		3.1	3.1	7.4	13.3
		Ground	0	6	0	9		--	0.9	--	1.3
		Total	*33*	*38*	*62*	*127*		*4.7*	*5.4*	*8.8*	*18.1*
	69	Major	19	10	12	38	101,212	1.9	1.0	1.2	3.8
		Minor	20	23	91	150		2.0	2.3	9.0	14.8
		Ground	0	11	1	19		--	1.1	0.1	1.9
		Total	*39*	*44*	*104*	*207*		*3.9*	*4.3*	*10.3*	*20.5*

(continued on next page)

*Includes Major Accidents, Minor Accidents or Incidents, Ground Accidents, and *Total Mishaps*.

Table 18 (continued)

Helicopter Series	FY	Mishap Type	Number: Pilot Error	Number: Other Personnel Error	Number: Materiel Failure	Number: Total	Flight-Hours	Rate (per 10,000 flight-hours): Pilot Error	Rate: Other Personnel Error	Rate: Materiel Failure	Rate: Total
(H-1, contd)	70	Major	15	12	14	32	124,370	1.2	1.0	1.1	2.6
		Minor	33	54	99	188		2.7	4.3	8.0	15.1
		Ground	1	27	5	38		0.1	2.2	0.4	3.1
		Total	*49*	*93*	*118*	*258*		*3.9*	*7.5*	*9.5*	*20.7*
	71	Major	10	5	13	23	128,031	0.8	0.4	1.0	1.8
		Minor	29	42	137	215		2.3	3.3	10.7	16.8
		Ground	0	19	1	23		--	1.5	0.1	1.8
		Total	*39*	*66*	*151*	*261*		*3.0*	*5.2*	*11.8*	*20.4*
	72	Major	14	9	6	19	121,034	1.2	0.7	0.5	1.6
		Minor	42	46	168	261		3.5	3.8	13.9	21.6
		Ground	0	38	4	45		--	3.1	0.3	3.7
		Total	*56*	*93*	*178*	*325*		*4.6*	*7.7*	*14.7*	*26.9*
	73	Major	4	2	1	4	110,322	0.4	0.2	0.1	0.4
		Minor	24	50	193	266		2.2	4.5	17.5	24.1
		Ground	0	18	0	19		--	1.6	--	1.7
		Total	*28*	*70*	*194*	*289*		*2.5*	*6.3*	*17.6*	*26.2*
H-2	63	Major	4	4	0	5	5,570	7.2	7.2	--	9.0
		Minor	2	2	1	3		3.6	3.6	1.8	5.4
		Ground	0	3	0	3		--	5.4	--	5.4
		Total	*6*	*9*	*1*	*11*		*10.8*	*16.2*	*1.8*	*19.7*

(continued on next page)

Table 18 (continued)

Helicopter Series	FY	Mishap Type	Number: Pilot Error	Number: Other Personnel Error	Number: Materiel Failure	Number: Total	Flight-Hours	Rate (per 10,000 flight-hours): Pilot Error	Rate: Other Personnel Error	Rate: Materiel Failure	Rate: Total
(H-2, contd)	64	Major	4	6	9	16	27,773	1.4	2.2	3.2	5.8
		Minor	5	12	21	35		1.8	4.3	7.6	12.6
		Ground	0	11	0	11		--	4.0	--	4.0
		Total	*9*	*29*	*30*	*62*		*3.2*	*10.4*	*10.8*	*22.3*
	65	Major	6	4	16	24	34,043	1.8	1.2	4.7	7.0
		Minor	14	8	12	34		4.1	2.3	3.5	10.0
		Ground	0	7	1	9		--	2.1	0.3	2.6
		Total	*20*	*19*	*29*	*67*		*5.9*	*5.6*	*8.5*	*19.7*
	66	Major	5	2	4	11	41,202	1.2	0.5	1.0	2.7
		Minor	8	7	14	29		1.9	1.7	3.4	7.0
		Ground	0	12	0	15		--	2.9	--	3.6
		Total	*13*	*21*	*18*	*55*		*3.2*	*5.1*	*4.4*	*13.3*
	67	Major	8	4	3	12	43,283	1.8	0.9	0.7	2.8
		Minor	13	5	23	36		3.0	1.2	5.3	8.3
		Ground	1	16	1	20		0.2	3.7	0.2	4.6
		Total	*22*	*25*	*27*	*68*		*5.1*	*5.8*	*6.2*	*15.7*
	68	Major	7	7	11	15	39,811	1.8	1.8	2.8	3.8
		Minor	10	15	32	56		2.5	3.8	8.0	14.1
		Ground	2	20	0	22		0.5	5.0	--	5.5
		Total	*19*	*42*	*43*	*93*		*4.6*	*10.5*	*10.8*	*23.4*

(continued on next page)

Table 18 (continued)

Heli-copter Series	FY	Mishap Type	Number				Flight-Hours	Rate (per 10,000 flight-hours)			
			Pilot Error	Other Personnel Error	Materiel Failure	Total		Pilot Error	Other Personnel Error	Materiel Failure	Total
(H-2, contd)	69	Major	4	6	4	10	36,371	1.1	1.6	1.1	2.7
		Minor	15	25	99	135		4.1	6.9	27.2	37.1
		Ground	0	40	3	47		--	11.0	0.8	12.9
		Total	*19*	*71*	*106*	*192*		*5.2*	*19.5*	*29.1*	*52.8*
	70	Major	2	1	2	5	30,753	0.7	0.3	0.7	1.6
		Minor	16	26	76	115		5.2	8.5	24.7	37.4
		Ground	0	35	1	38		--	11.4	0.3	12.4
		Total	*18*	*62*	*79*	*158*		*5.9*	*20.2*	*25.7*	*51.4*
	71	Major	1	0	1	1	27,500	0.4	--	0.4	0.4
		Minor	18	19	87	123		6.5	6.9	31.6	44.7
		Ground	0	17	1	19		--	6.2	0.4	6.9
		Total	*19*	*36*	*89*	*143*		*6.9*	*13.1*	*32.4*	*52.0*
	72	Major	1	0	3	4	23,560	0.4	--	1.3	1.7
		Minor	16	25	87	126		6.8	10.6	36.9	53.5
		Ground	0	35	3	39		--	14.9	1.3	16.6
		Total	*17*	*60*	*93*	*169*		*7.2*	*25.5*	*39.5*	*71.7*
	73	Major	5	4	2	6	26,714	1.9	1.5	0.7	2.2
		Minor	8	31	148	189		3.0	11.6	55.4	70.7
		Ground	1	24	3	31		0.4	9.0	1.1	11.6
		Total	*14*	*59*	*153*	*226*		*5.2*	*22.1*	*57.3*	*84.6*

(continued on next page)

Table 18 (continued)

Heli-copter Series	FY	Mishap Type	Number: Pilot Error	Number: Other Personnel Error	Number: Materiel Failure	Number: Total	Flight-Hours	Rate (per 10,000 flight-hours): Pilot Error	Rate: Other Personnel Error	Rate: Materiel Failure	Rate: Total
H-3	61	Major	1	0	0	1	2,316	4.3	--	--	4.3
		Minor	2	0	1	4		8.6	--	4.3	17.3
		Ground	0	3	0	3		--	13.0	--	13.0
		Total	*3*	*3*	*1*	*8*		*13.0*	*13.0*	*4.3*	*34.5*
	62	Major	2	2	2	4	23,533	0.8	0.8	0.8	1.7
		Minor	3	4	4	11		1.3	1.7	1.7	4.7
		Ground	1	13	2	16		0.4	5.5	0.8	6.8
		Total	*6*	*19*	*8*	*31*		*2.5*	*8.1*	*3.4*	*13.2*
	63	Major	7	2	5	11	47,102	1.5	0.4	1.1	2.3
		Minor	13	9	7	21		2.8	1.9	1.5	4.5
		Ground	0	17	0	22		--	3.6	--	4.7
		Total	*20*	*28*	*12*	*54*		*4.2*	*5.9*	*2.5*	*11.5*
	64	Major	4	2	3	9	77,882	0.5	0.3	0.4	1.2
		Minor	21	19	22	64		2.7	2.4	2.8	8.2
		Ground	1	37	4	46		0.1	4.8	0.5	5.9
		Total	*26*	*58*	*29*	*119*		*3.3*	*7.4*	*3.7*	*15.3*
	65	Major	3	3	4	7	82,050	0.4	0.4	0.5	0.9
		Minor	27	25	61	110		3.3	3.0	7.4	13.4
		Ground	0	29	6	30		--	3.5	0.7	3.7
		Total	*30*	*57*	*71*	*147*		*3.7*	*6.9*	*8.7*	*17.9*

(continued on next page)

Table 18 (continued)

Heli-copter Series	FY	Mishap Type	Number				Flight-Hours	Rate (per 10,000 flight-hours)			
			Pilot Error	Other Personnel Error	Materiel Failure	Total		Pilot Error	Other Personnel Error	Materiel Failure	Total
(H-3, contd)	66	Major	2	1	3	6	88,306	0.2	0.1	0.3	0.7
		Minor	18	22	65	103		2.0	2.5	7.4	11.7
		Ground	2	30	2	34		0.2	3.4	0.2	3.9
		Total	*22*	*53*	*70*	*143*		*2.5*	*6.0*	*7.9*	*16.2*
	67	Major	5	3	5	14	89,684	0.6	0.3	0.6	1.6
		Minor	21	24	56	93		2.3	2.7	6.2	10.4
		Ground	3	28	0	30		0.3	3.1	--	3.3
		Total	*29*	*55*	*61*	*137*		*3.2*	*6.1*	*6.8*	*15.5*
	68	Major	3	4	2	10	93,186	0.3	0.4	0.2	1.1
		Minor	44	43	96	167		4.7	4.6	10.3	17.9
		Ground	0	37	8	47		--	4.0	0.9	5.0
		Total	*47*	*84*	*106*	*224*		*5.0*	*9.0*	*11.4*	*24.0*
	69	Major	5	4	5	8	98,192	0.5	0.4	0.5	0.8
		Minor	39	46	140	216		4.0	4.7	14.3	27.0
		Ground	0	68	6	76		--	6.9	0.6	7.7
		Total	*44*	*118*	*151*	*300*		*4.5*	*12.0*	*15.4*	*30.6*
	70	Major	6	3	6	10	78,067	0.8	0.4	0.8	1.3
		Minor	22	36	101	161		2.8	4.6	12.9	20.6
		Ground	0	48	2	57		--	6.1	0.3	7.3
		Total	*28*	*87*	*109*	*228*		*3.6*	*11.1*	*14.0*	*29.2*

(continued on next page)

Table 18 (continued)

Helicopter Series	FY	Mishap Type	Number				Flight-Hours	Rate (per 10,000 flight-hours)			
			Pilot Error	Other Personnel Error	Materiel Failure	Total		Pilot Error	Other Personnel Error	Materiel Failure	Total
(H-3, contd)	71	Major	5	7	5	11	69,295	0.7	1.0	0.7	1.6
		Minor	22	43	145	209		3.2	6.2	20.9	30.2
		Ground	0	63	13	77		--	9.1	1.9	11.1
		Total	*27*	*113*	*163*	*297*		*3.9*	*16.3*	*23.5*	*42.9*
	72	Major	4	0	3	6	88,538	0.5	--	0.3	0.7
		Minor	31	65	391	490		3.5	7.3	44.2	55.3
		Ground	2	75	8	89		0.2	8.5	0.9	10.1
		Total	*37*	*140*	*402*	*585*		*4.2*	*15.8*	*45.4*	*66.1*
	73	Major	4	6	2	9	95,670	0.4	0.6	0.2	0.9
		Minor	33	97	383	507		3.4	10.1	40.0	53.0
		Ground	1	71	4	81		0.1	7.4	0.4	8.5
		Total	*38*	*174*	*389*	*597*		*4.0*	*18.2*	*40.7*	*62.4*
H-46	65	Major	1	0	0	1	9,034	1.1	--	--	1.1
		Minor	2	2	8	12		2.2	2.2	8.9	13.3
		Ground	0	1	0	1		--	1.1	--	1.1
		Total	*3*	*3*	*8*	*14*		*3.3*	*3.3*	*8.9*	*15.5*
	66	Major	2	1	0	3	33,442	0.6	0.3	--	0.9
		Minor	13	14	32	60		3.9	4.2	9.6	17.9
		Ground	1	9	6	17		0.3	2.7	1.8	5.1
		Total	*16*	*24*	*38*	*80*		*4.8*	*7.2*	*11.4*	*23.9*

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Table 18 (continued)

Heli-copter Series	FY	Mishap Type	Number: Pilot Error	Number: Other Personnel Error	Number: Materiel Failure	Number: Total	Flight-Hours	Rate (per 10,000 flight-hours): Pilot Error	Rate: Other Personnel Error	Rate: Materiel Failure	Rate: Total
(H-46, contd)	67	Major	6	4	6	17	75,108	0.8	0.5	0.8	2.3
		Minor	27	37	57	153		3.6	4.9	7.6	20.4
		Ground	2	19	3	25		0.3	2.5	0.4	3.3
		Total	*35*	*60*	*66*	*195*		*4.7*	*8.0*	*8.8*	*26.0*
	68	Major	10	9	17	26	91,917	1.1	1.0	1.8	2.8
		Minor	18	37	52	108		2.0	4.0	5.7	11.7
		Ground	3	29	6	43		0.3	3.2	0.7	4.7
		Total	*31*	*75*	*75*	*177*		*3.4*	*8.2*	*8.2*	*19.3*
	69	Major	15	16	11	32	161,543	0.9	1.0	0.7	2.0
		Minor	55	66	236	384		3.4	4.1	14.6	23.8
		Ground	0	38	2	46		--	2.4	0.1	2.8
		Total	*70*	*120*	*249*	*462*		*4.3*	*7.4*	*15.4*	*28.6*
	70	Major	13	13	7	24	140,247	0.9	0.9	0.5	1.7
		Minor	67	92	299	483		4.8	6.6	21.3	34.4
		Ground	0	27	6	86		--	1.9	0.4	6.1
		Total	*80*	*132*	*312*	*593*		*5.7*	*9.4*	*22.2*	*42.3*
	71	Major	4	6	5	10	132,350	0.3	0.5	0.4	0.8
		Minor	50	65	198	334		3.8	4.9	15.0	25.2
		Ground	3	30	4	41		0.2	2.3	0.3	3.1
		Total	*57*	*101*	*207*	*385*		*4.3*	*7.6*	*15.6*	*29.1*

(continued on next page)

Table 18 (continued)

Helicopter Series	FY	Mishap Type	Number: Pilot Error	Number: Other Personnel Error	Number: Materiel Failure	Number: Total	Flight-Hours	Rate (per 10,000 flight-hours): Pilot Error	Rate: Other Personnel Error	Rate: Materiel Failure	Rate: Total
(H-46, contd)	72	Major	3	2	2	9	95,046	0.3	0.2	0.2	0.9
		Minor	29	46	175	258		3.1	4.8	18.4	27.1
		Ground	1	46	5	55		0.1	4.8	0.5	5.8
		Total	*33*	*94*	*182*	*322*		*3.5*	*9.9*	*19.1*	*33.9*
	73	Major	3	2	1	6	93,971	0.3	0.2	0.1	0.6
		Minor	35	82	215	346		3.7	8.7	22.9	36.8
		Ground	1	38	6	46		0.1	4.0	0.6	4.9
		Total	*39*	*122*	*222*	*398*		*4.2*	*13.0*	*23.6*	*42.4*
H-53	67	Major	2	1	0	2	9,006	2.2	1.1	--	2.2
		Minor	6	9	34	47		6.7	10.0	37.8	52.3
		Ground	0	0	0	0		--	--	--	--
		Total	*8*	*10*	*34*	*49*		*8.9*	*11.1*	*37.8*	*54.5*
	68	Major	7	3	1	8	26,392	2.7	1.1	0.4	3.0
		Minor	10	16	49	69		3.8	6.1	18.6	26.1
		Ground	0	13	4	17		--	4.9	1.5	6.4
		Total	*17*	*32*	*54*	*94*		*6.4*	*12.1*	*20.5*	*35.6*
	69	Major	3	4	1	6	34,046	0.9	1.2	0.3	1.8
		Minor	35	30	67	119		10.3	8.8	19.7	35.0
		Ground	1	17	0	18		0.3	5.0	--	5.3
		Total	*39*	*51*	*68*	*143*		*11.5*	*15.0*	*20.0*	*42.0*

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Table 18 (concluded)

Heli-copter Series	FY	Mishap Type	Number: Pilot Error	Number: Other Personnel Error	Number: Materiel Failure	Number: Total	Flight-Hours	Rate (per 10,000 flight-hours): Pilot Error	Rate: Other Personnel Error	Rate: Materiel Failure	Rate: Total
(H-53, contd)	70	Major	3	0	1	4	40,251	0.7	--	0.2	0.9
		Minor	22	29	89	132		5.5	7.2	22.1	32.8
		Ground	0	29	3	31		--	7.2	0.7	7.7
		Total	*25*	*58*	*93*	*167*		*6.2*	*14.4*	*23.0*	*40.5*
	71	Major	5	1	2	6	43,798	1.1	0.2	0.5	1.4
		Minor	30	55	141	204		6.8	12.6	32.2	46.6
		Ground	1	36	6	41		0.2	8.2	1.4	9.4
		Total	*36*	*92*	*149*	*251*		*8.2*	*21.0*	*34.0*	*57.3*
	72	Major	3	3	1	4	46,714	0.6	0.6	0.2	0.9
		Minor	18	55	195	253		3.9	11.8	41.7	54.2
		Ground	1	38	13	50		0.2	8.1	2.8	10.7
		Total	*22*	*96*	*209*	*307*		*4.7*	*20.6*	*44.7*	*65.7*
	73	Major	4	5	7	11	43,969	0.9	1.1	1.6	2.5
		Minor	24	59	248	318		5.5	13.4	56.4	72.4
		Ground	2	52	10	61		0.5	11.8	2.3	13.9
		Total	*30*	*116*	*265*	*390*		*6.8*	*26.4*	*60.3*	*88.7*

Source: Naval Safety Center, Norfolk, Virginia

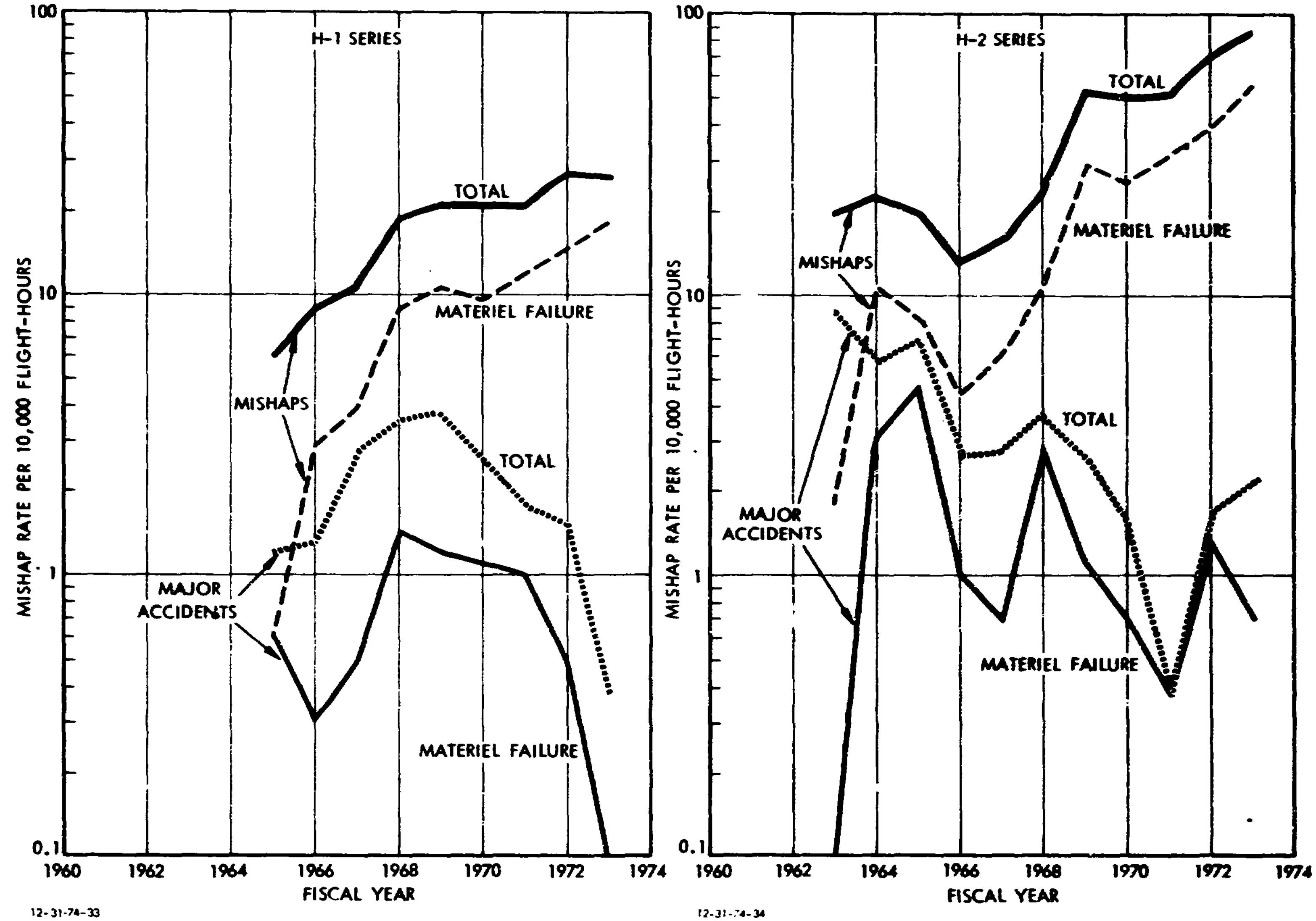

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Figure 39. MISHAP RATES FOR NAVY HELICOPTERS

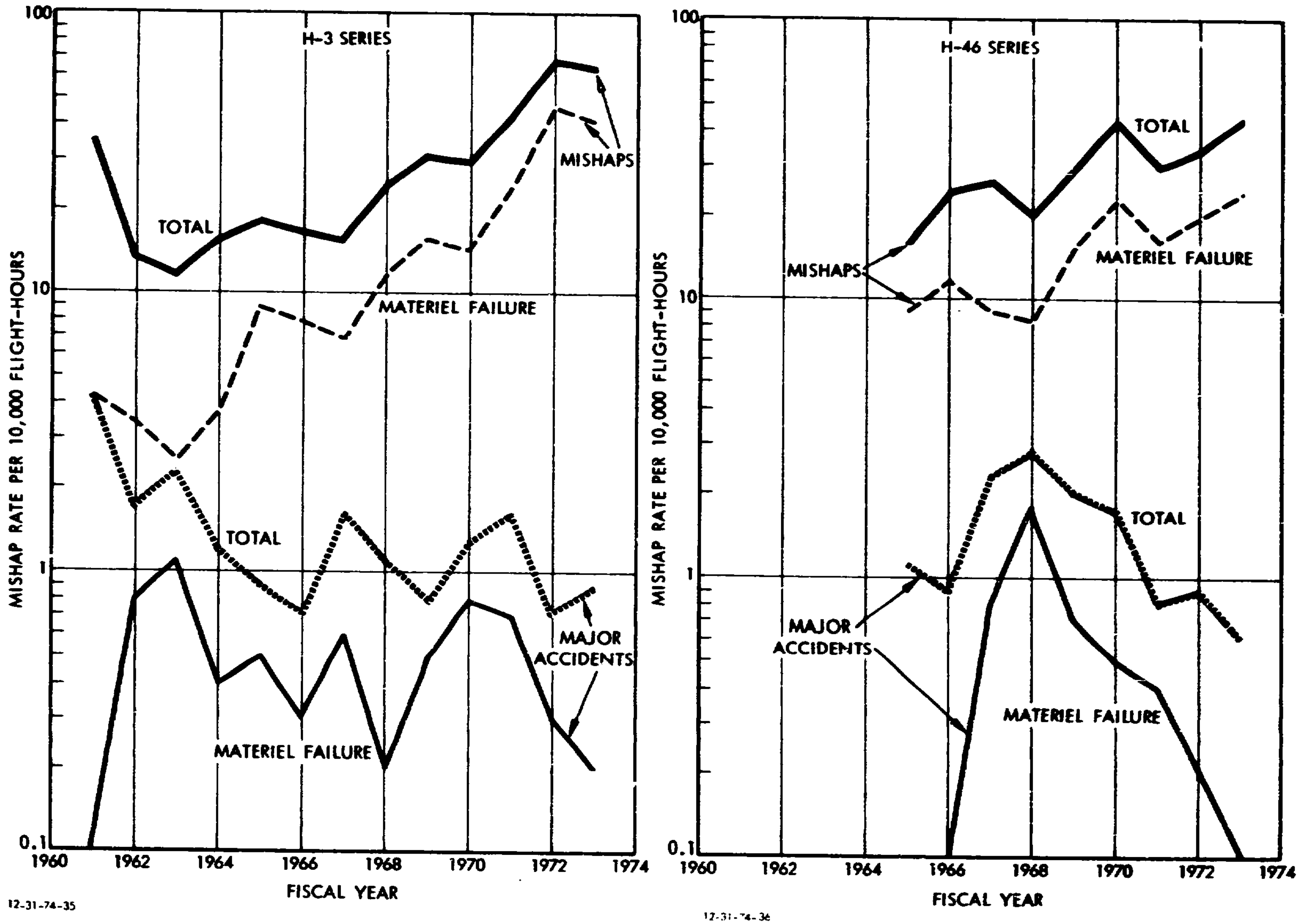

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Figure 39 (continued)

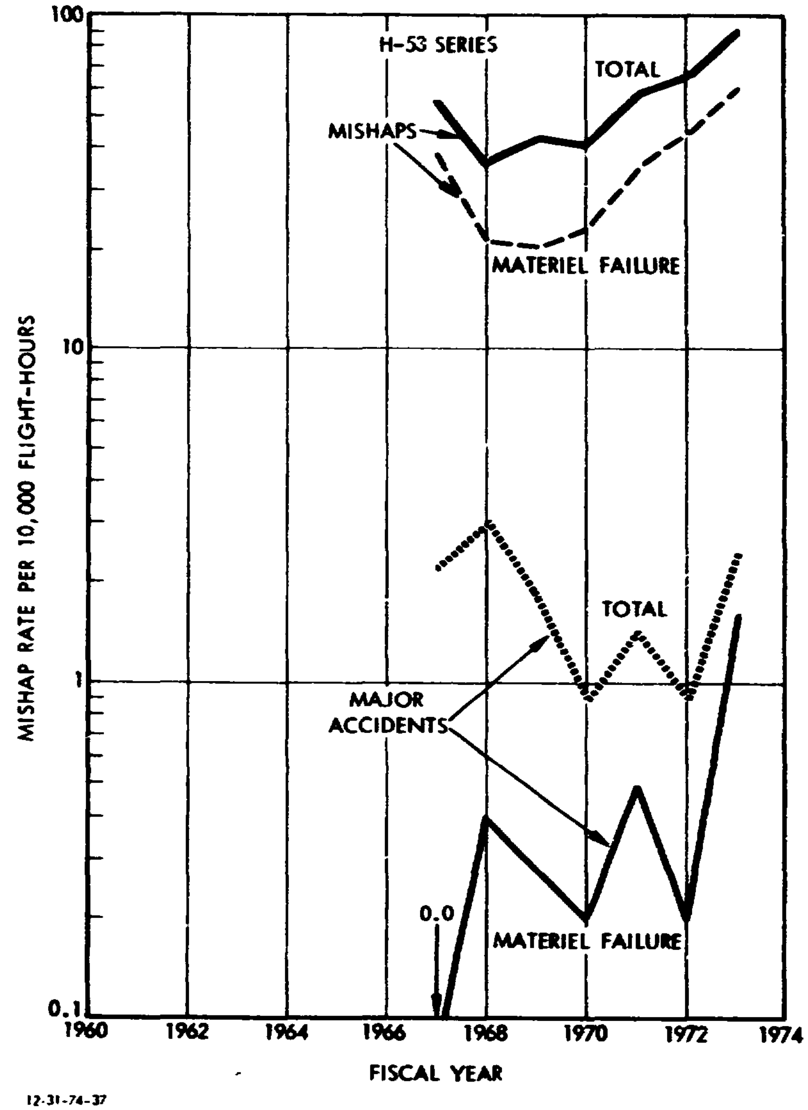

Figure 39 (concluded)

and (2) their degree of eagerness decreases with the age of the the aircraft. Figures 40-44 were taken directly from a NSC memorandum; on these plots the rate scale (per 10,000 flight-hours) is linear. They show by system the breakdown of materiel-caused mishaps. Although there is considerable crossing over of the system rates, in general the system rates tend to move with the overall materiel rate. The overall materiel rate in the top panel of these plots corresponds to the mishap rate involving materiel of Figure 39.

3. Air Force

The Air Force Logistics Command, ACVMM, Wright-Patterson AFB, Ohio, supplied IDA with tapes covering Accident, Incident and Emergency Unsatisfactory Material Report (AIE) data. Per our request, we were to have been provided these data covering calendar years 1970-73. Upon reading the tapes supplied us, we learned that no data were included for 1970 and 1972--and only part-year coverage for 1971 and 1973. Consequently, the information contained in the tapes provided was not sufficient to construct AIE time trends.

B. EFFECT OF HELICOPTER EMPTY WEIGHT

Since large helicopters have more parts that could fail or malfunction, one could hypothesize that large helicopters would have more accidents or mishaps than small helicopters. Accordingly, we felt it would be of interest to investigate mishap rates as a function of empty weight.

Figures 38-44 indicate that mishap rates vary sharply from year to year. Accordingly, in investigating the effect of helicopter weight on mishap rates, we have used the average mishap rates for the last three fiscal years (FYs 1971-73).

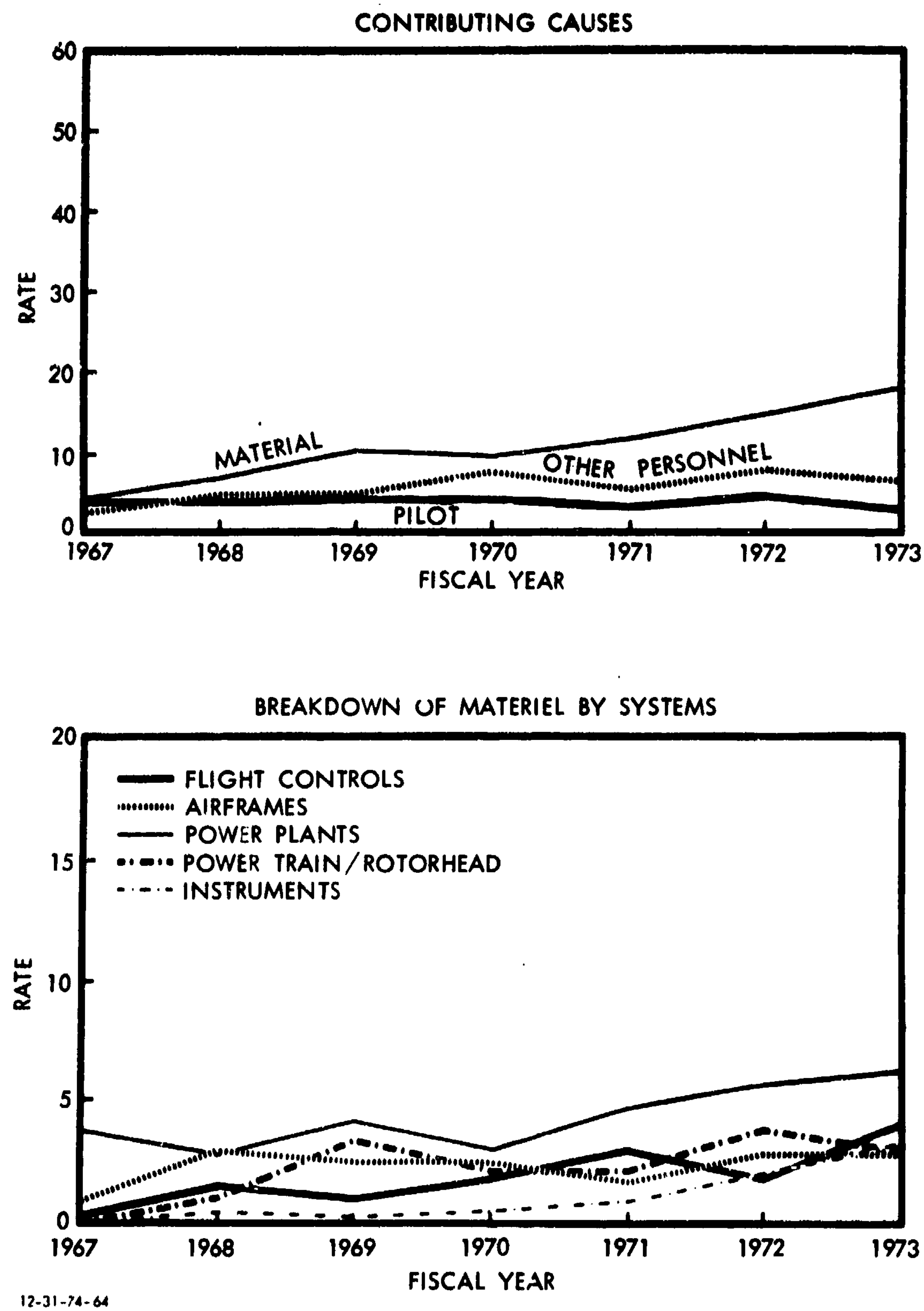

Figure 40. MISHAP RATES FOR THE NAVY H-1 SERIES (BY CAUSE AND BY SYSTEM)

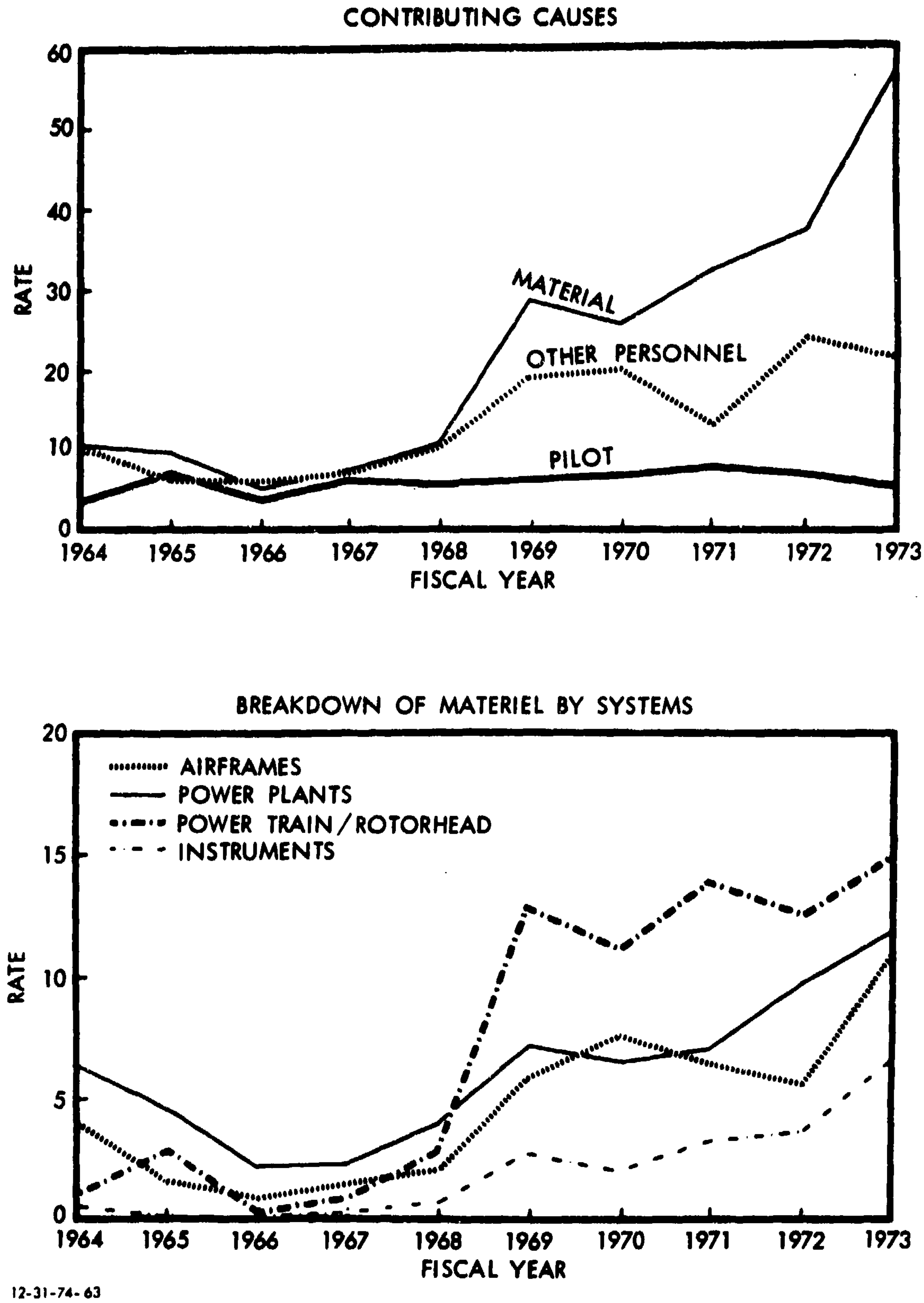

Figure 41. MISHAP RATES FOR THE NAVY H-2 SERIES (BY CAUSE AND BY SYSTEM)

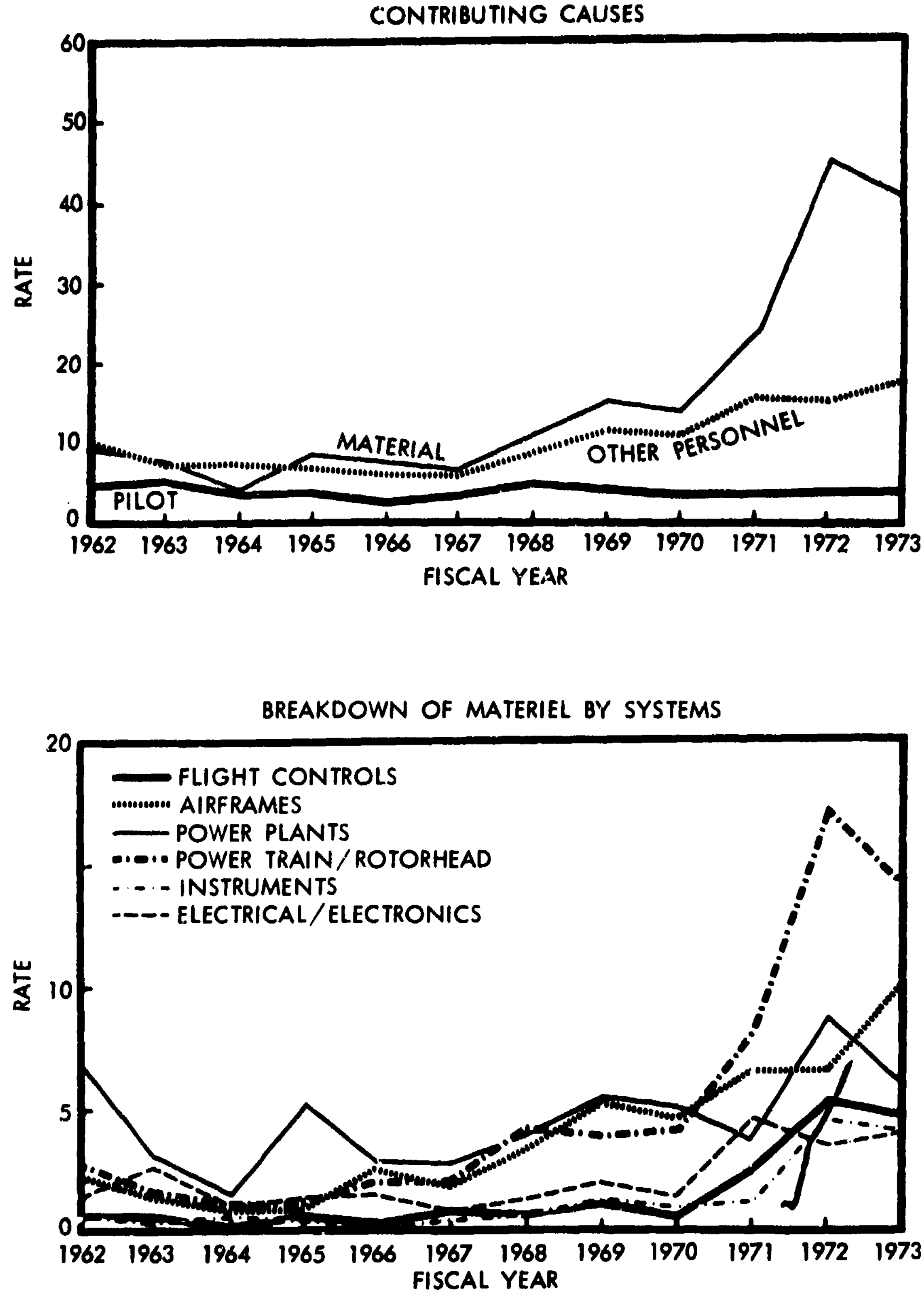

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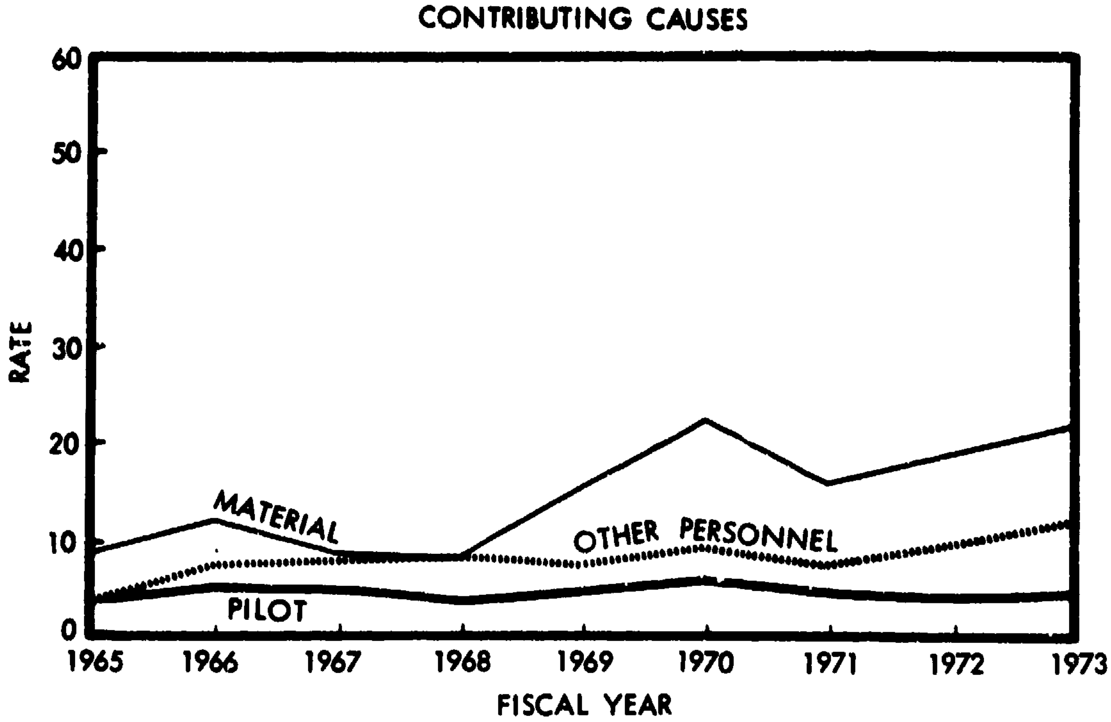
Figure 42. MISHAP RATES FOR THE NAVY H-3 SERIES (BY CAUSE AND BY SYSTEM)



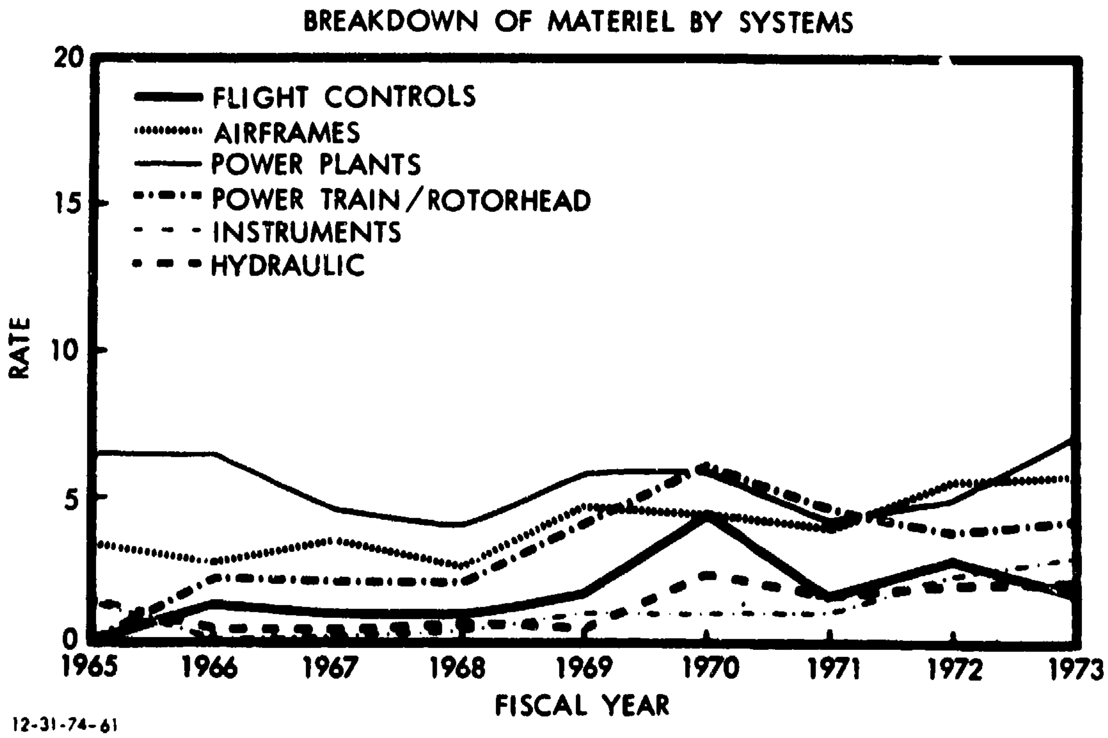


Figure 43. MISHAP RATES FOR THE NAVY H-46 SERIES (BY CAUSE AND BY SYSTEM)

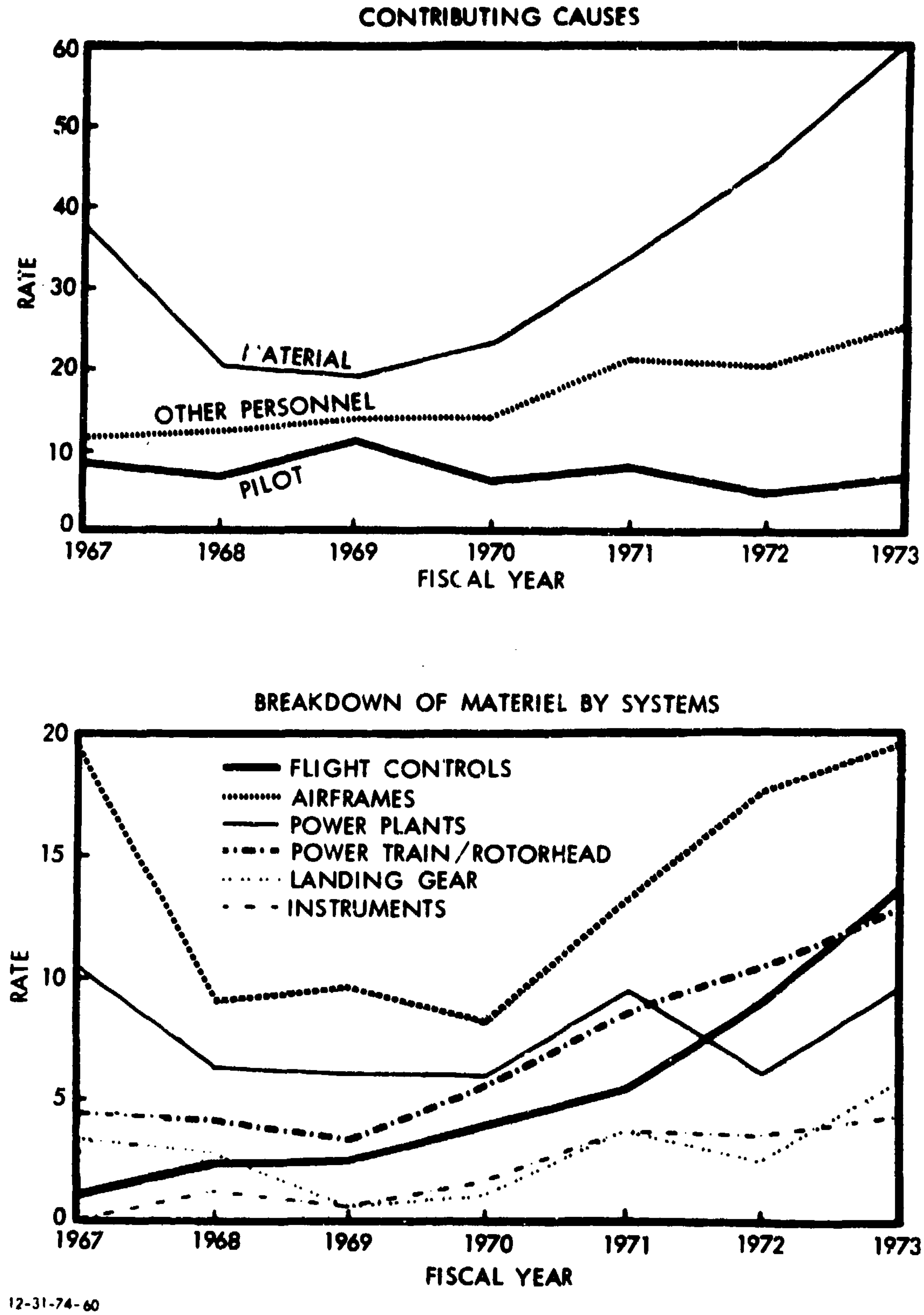


Figure 44. MISHAP RATES FOR THE NAVY H-53 SERIES (BY CAUSE AND BY SYSTEM)

Helicopter weights within a family of helicopters (such as the Bell H-1 family) vary by individual model. Further, the composition of a Service's fleet is constantly changing as later models are procured and earlier models are retired. In Tables 19[1] and 20, we have estimated average empty weight for each helicopter family and shown the average mishap rates for the past three years. These data are plotted in Figures 45 and 46. These plots indicate that accident rates seem to be independent of aircraft weight, while all mishaps (both those involving materiel and total) seem to increase with size.

Of course, there are many other factors that can affect these rates. The type of mission, age of the fleet, geographical environment, etc., can be particularly important in accident rates.

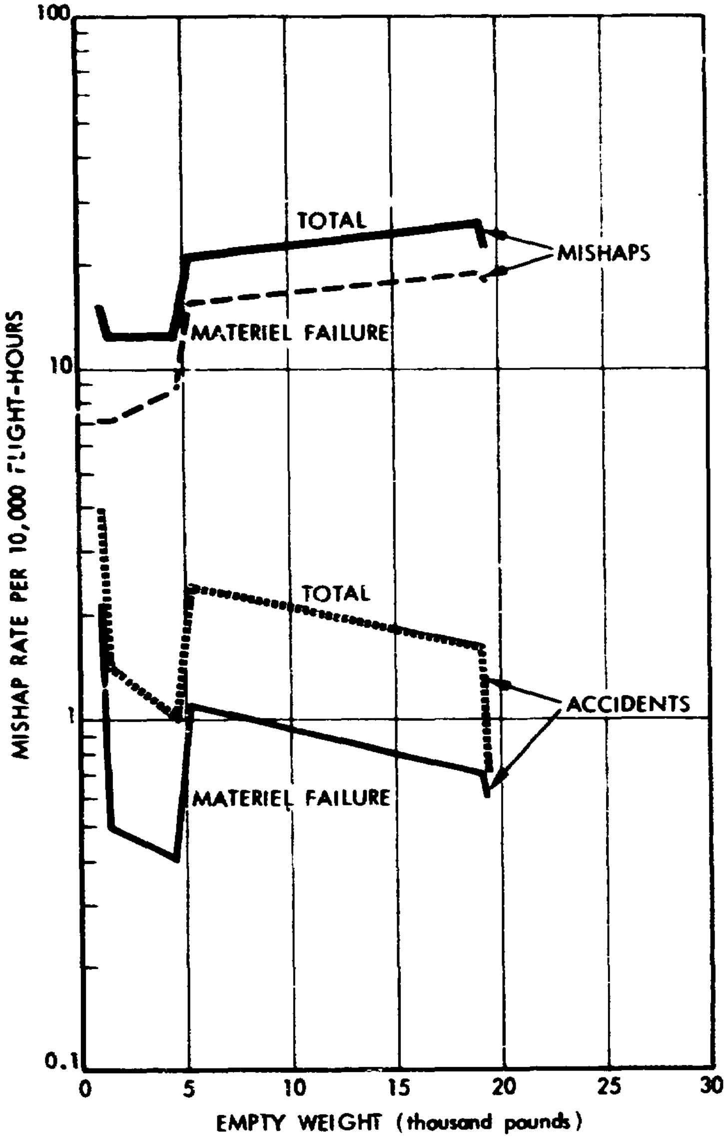
[1]The CH-37 was dropped from the Army helicopter types, since it was the only piston-powered Army helicopter and was being phased out of service during this period.

Table 19. AVERAGE MISHAP RATES FOR ARMY HELICOPTERS, FYs 1971-73
[Per 10,000 flight-hours]

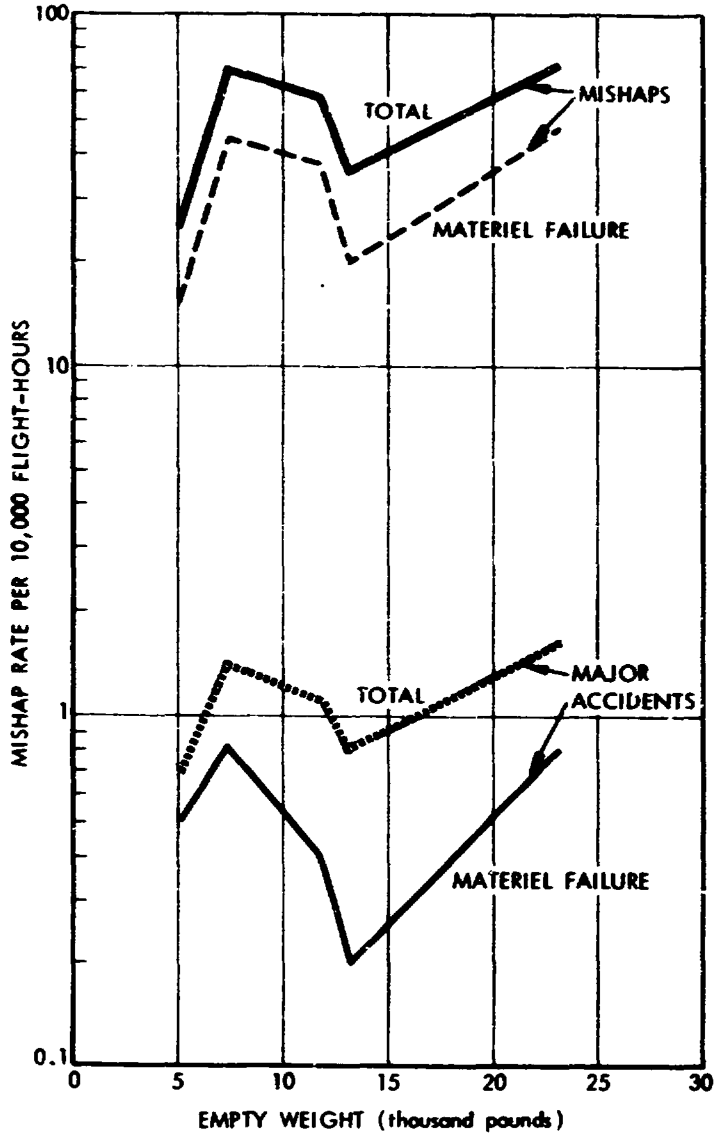
Heli-copter Type	Average Empty Weight	Accidents		Mishaps	
		Materiel Failure	Total	Materiel Failure	Total
UH-1	4,700	0.4	1.0	8.6	12.1
AH-1	5,300	1.1	2.4	15.2	20.9
OH-6	1,200	2.1	4.0	7.2	14.9
CH-47	19,400	0.6	0.7	17.7	22.2
CH-54	19,200	0.7	1.6	18.4	25.8
OH-58	1,500	0.5	1.4	7.1	12.1

Table 20. AVERAGE MISHAP RATES FOR NAVY HELICOPTERS, FYs 1971-73
[Per 10,000 flight-hours]

Heli-copter Type	Average Empty Weight	Accidents		Mishaps	
		Materiel Failure	Total	Materiel Failure	Total
H-1	5,000	0.5	6.8	14.7	24.5
H-2	7,300	0.8	1.4	43.1	69.4
H-3	11,800	0.4	1.1	36.5	57.1
H-46	13,200	0.2	0.8	19.4	35.1
H-53	23,200	0.8	1.6	46.3	70.6



12-31-74-38
Figure 45. MISHAP RATES VERSUS EMPTY WEIGHT FOR ARMY HELICOPTERS



12-31-74-39
Figure 46. MISHAP RATES VERSUS EMPTY WEIGHT FOR NAVY HELICOPTERS

Chapter III

ANALYSIS OF AH-56A (CHEYENNE) RELIABILITY IMPROVEMENT

The AH-56A was a high-speed compound helicopter that was based on very advanced rotary-wing technology. It was flown in a development program that lasted almost five years before the helicopter was canceled without ever reaching service use. Helicopter programs normally require about three years from first flight to service use. Accordingly, it is possible that the reliability growth of the AH-56A may not have been representative of programs that successfully enter service use after about three years. Compared with the other development programs for which data are available, it appears that AH-56A reliability growth may have been somewhat slower than that of "successful" development programs.

A. TOTAL SYSTEM

The data used in this analysis of AH-56A reliability improvement come from the "Deducted Item Failure List" and the "Residual Item Failure List" (Ref. [14, Vol. III, Appendixes D and F, resp.]). This Lockheed report divides the AH-56A aircraft into six basic categories, identified as Modes 1 through 6 (Ref. [14, Vol. III, pp. v-vi]), as follows:

Mode 1: Airframe
Landing gear
Power plant
Power transmission
Rotors and propellers
Hydraulic power
Fuel systems

Flight controls
Utilities (mechanical)
Auxiliary power plant

Mode 2: Instruments
Electrical power system
Special instrumentations and displays
Utilities (electrical)
Fault location and warning system

Mode 3: Communications

Mode 4: Navigation system
Intercom
Swiveling gunner's station
Pilot's fire control
Stores control

Mode 5: Computer central complex

Mode 6: Gun and associated systems
Rockets and associated systems
Missiles and associated systems

By grouping the system codes contained in a table [ibid., pp. ix-xi], we were able to further subdivide Mode 1 into the following categories:

Mode 1a: Airframe components
Landing gear
Hydraulic power
Fuel systems
Flight controls
Utilities (mechanical)

Mode 1b: Rotors and propellers

Mode 1c: Gear boxes and drives

Mode 1d: Power plant
Auxiliary power plant

The monthly flight-hour data (supplied to us by Lockheed and presented in Table 21) covers 52 months of flight testing, which began in September 1967 and continued through December 1971. We have counted only those failures that occurred during this period on aircraft that were being flight tested. Aircraft serial number 1001 (a Ground Test Vehicle) was never flown. Similarly, aircraft serial number 1004 (used by Lockheed to conduct maintenance training and verification) was never flown.

Table 21. MONTHLY AND CUMULATIVE FLIGHT-HOURS FOR THE AH-56A (CHEYENNE)

Month	Flight-Hours		Month	Flight-Hours	
	Monthly	Cumulative		Monthly	Cumulative
9/67	1.4	1.4	11/69	12.3	535.6
10/67	3.3	4.7	12/69	26.0	561.6
11/67	5.1	9.8	1/70	7.2	568.8
12/67	8.2	18.0	2/70	21.2	590.0
1/68	22.2	40.2	3/70	28.1	618.1
2/68	14.2	54.4	4/70	39.3	657.4
3/68	5.5	59.9	5/70	25.7	683.1
4/68	20.6	80.5	6/70	25.0	708.1
5/68	3.4	83.9	7/70	15.0	723.1
6/68	28.9	112.8	8/70	30.2	753.3
7/68	28.3	141.1	9/70	32.8	786.1
8/68	10.5	151.6	10/70	16.7	802.8
9/68	4.1	155.7	11/70	31.8	834.6
10/68	16.7	172.4	12/70	45.7	880.3
11/68	46.8	219.2	1/71	49.5	929.8
12/68	48.4	267.6	2/71	28.2	958.0
1/69	61.3	328.9	3/71	22.6	980.6
2/69	78.6	407.5	4/71	46.4	1,027.0
3/69	34.8	442.3	5/71	23.5	1,050.5
4/69	0.0	442.3	6/71	40.8	1,091.3
5/69	0.9	443.2	7/71	36.8	1,128.1
6/69	4.9	448.1	8/71	36.9	1,165.0
7/69	9.7	457.8	9/71	63.7	1,228.7
8/69	7.0	464.8	10/71	52.5	1,281.2
9/69	31.5	496.3	11/71	72.5	1,353.7
10/69	27.0	523.3	12/71	72.3	1,426.0

We have excluded all failures that occurred on these two vehicles. Also, we have excluded all failures that occurred before flight testing began in September 1967. Thus, the data in Table 22 show a total of 1,553 failures from September 1967 through December 1971, which compares with a total of 1,770 primary failures reported by Lockheed [14, Vol. I, p. xii]. The difference in the failure count is due to failures on serial numbers 1001 and 1004, which Lockheed counted but we did not. It is to be noted that we have combined the deducted failures and the residual failures into a single list, to obtain a total failure count for each month of flight testing.

1. Contractual Reliability Goals and Measurement Procedures

For the purpose of standardizing the measurement of mission reliability, the CHEYENNE reliability goals were based on the long-endurance (2.5-hour) escort mission. It consists of the following sequence of events:

(1) Take-off.

(2) Hover (2 minutes).

(3) Cruise (195 knots for 30 minutes, at not more than normal rated power).

(4) Hover (10 minutes).

(5) Dash (212±4 knots for 15 minutes).

(6) Cruise (140 knots for 90 minutes).

(7) Hover (2 minutes).

(8) Land.

All mission- and system-reliability requirements were established with this long-range mission as a base [ibid., p. 1]. The reliability goals stated in terms of this mission were--

(1) *Mission Reliability*. Ninety-four (94) percent mission reliability, exclusive of the armament subsystems, to be demonstrated at the 90-percent confidence level (see Paragraph 7.4.4.2, Appendix A, below).

(2) *System Reliability*. Seventy-nine (79) percent system reliability, exclusive of the armament subsystems, to

Table 22. MONTHLY AND CUMULATIVE FAILURES (WITH CUMULATIVE RATE) FOR THE AH-56A (CHEYENNE) TOTAL SYSTEM

Monthly Failures		Cumulative Failures		Monthly Failures		Cumulative Failures	
Month	Number	Number	Rate	Month	Number	Number	Rate
9/67	7	7	5.000	11/69	18	672	1.255
10/67	10	17	3.617	12/69	17	689	1.227
11/67	11	28	2.857	1/70	18	707	1.243
12/67	9	37	2.056	2/70	32	739	1.253
1/68	8	45	1.119	3/70	22	761	1.231
2/68	19	64	1.176	4/70	41	802	1.220
3/68	17	81	1.352	5/70	32	834	1.221
4/68	34	115	1.429	6/70	40	874	1.234
5/68	22	137	1.633	7/70	29	903	1.249
6/68	32	169	1.498	8/70	52	955	1.268
7/68	51	220	1.559	9/70	54	1,009	1.284
8/68	26	246	1.623	10/70	42	1,051	1.309
9/68	23	269	1.728	11/70	37	1,088	1.304
10/68	22	291	1.688	12/70	63	1,151	1.308
11/68	35	326	1.487	1/71	37	1,188	1.278
12/68	32	358	1.338	2/71	30	1,218	1.271
1/69	42	400	1.216	3/71	40	1,258	1.283
2/69	38	438	1.075	4/71	30	1,288	1.254
3/69	24	462	1.045	5/71	23	1,311	1.248
4/69	7	469	1.060	6/71	32	1,343	1.231
5/69	22	491	1.108	7/71	26	1,369	1.214
6/69	23	514	1.147	8/71	36	1,405	1.206
7/69	29	543	1.186	9/71	40	1,445	1.176
8/69	37	580	1.248	10/71	39	1,484	1.158
9/69	35	615	1.239	11/71	41	1,525	1.127
10/69	39	654	1.250	12/71	28	1,553	1.089

be demonstrated at the 90-percent confidence level (see Paragraph 7.4.5.2, Appendix A, below; and Ref. [14, Vol. III, p. H-2]).

Procedures used by Lockheed to determine the failure count and to measure mission and system reliability are quoted verbatim in Appendix A (below).

2. Data Analysis by Lockheed

Before presenting our own analysis of the AH-56A reliability data, we shall present the result of the analysis performed by the AH-56A contractor, Lockheed Aircraft Corporation.

Lockheed reported the following measurements:

- Mission Reliability at 92% based on a statistical confidence level of 90% with data collected through 1,884 flight hours....
- System Reliability at 70% based on a statistical confidence level of 90% with data collected through 1,884 flight hours.... [14, Vol. I, p. xi]

Lockheed noted that these 1,884 flight-hours include run time on the Ground Test Vehicle (GTV), Serial Number 1001, while the test-flight-hour data in Table 21 do not include run time on the GTV.

Lockheed makes the following statement:

> Of the 1,770 primary failures identified during this development and measurement program, 1,487 or 84%, have been corrected by redesign to prevent recurrence. The remaining 283 failures continue to be analyzed for effective corrective actions. [14, Vol. I, p. xii]

The reliability computations quoted above were obtained by a Monte Carlo computer simulation in which Government Furnished Material (GFM) components were assumed to have fixed failure rates (so-called "par values") "to allow the Government to assess the Contractor's individual reliability effort without the influence of GFM operation" [14, Vol. I, p. 2]. Figure 47 (from [14, Vol. I, p. 4]) shows graphically the results of the

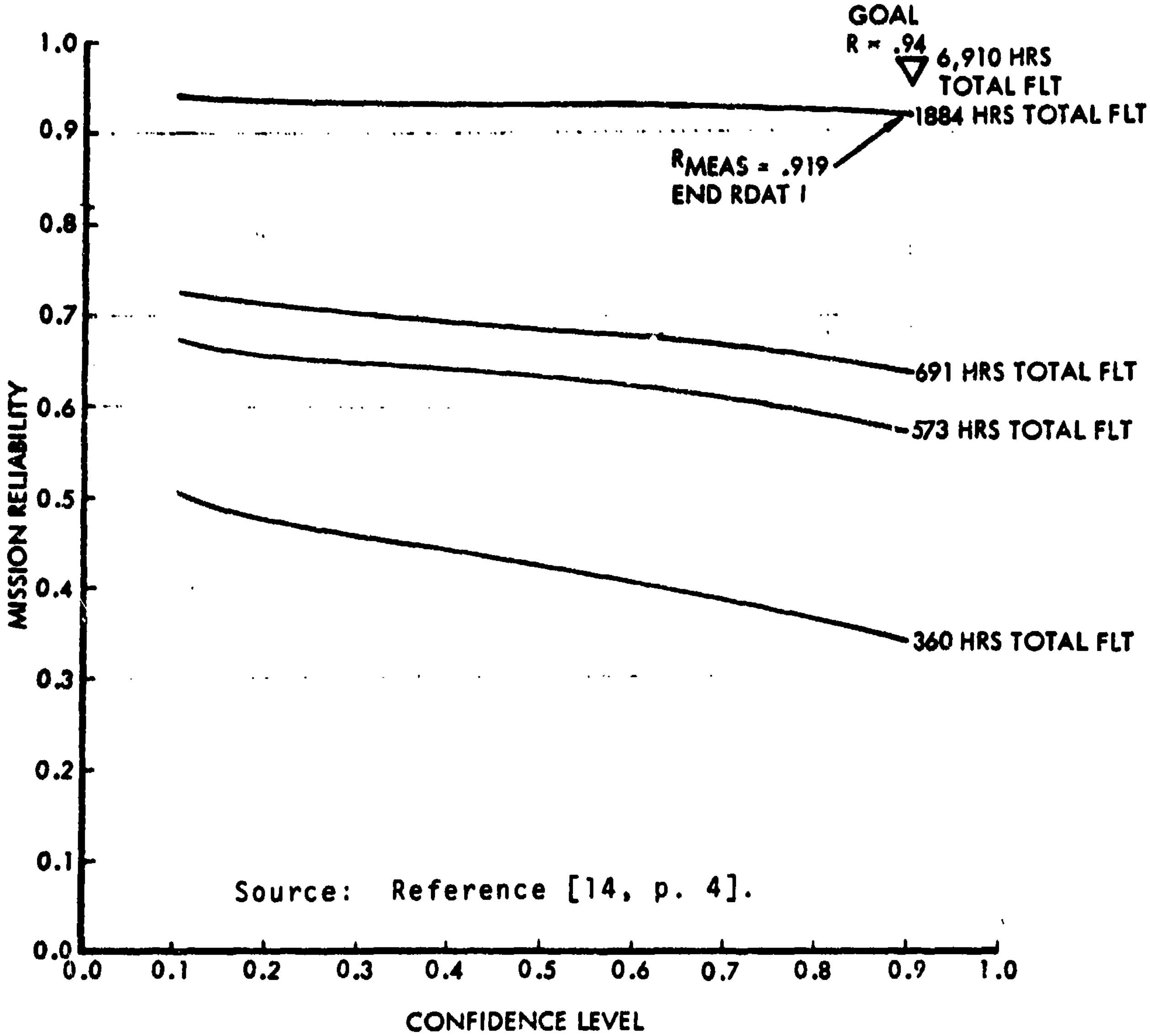
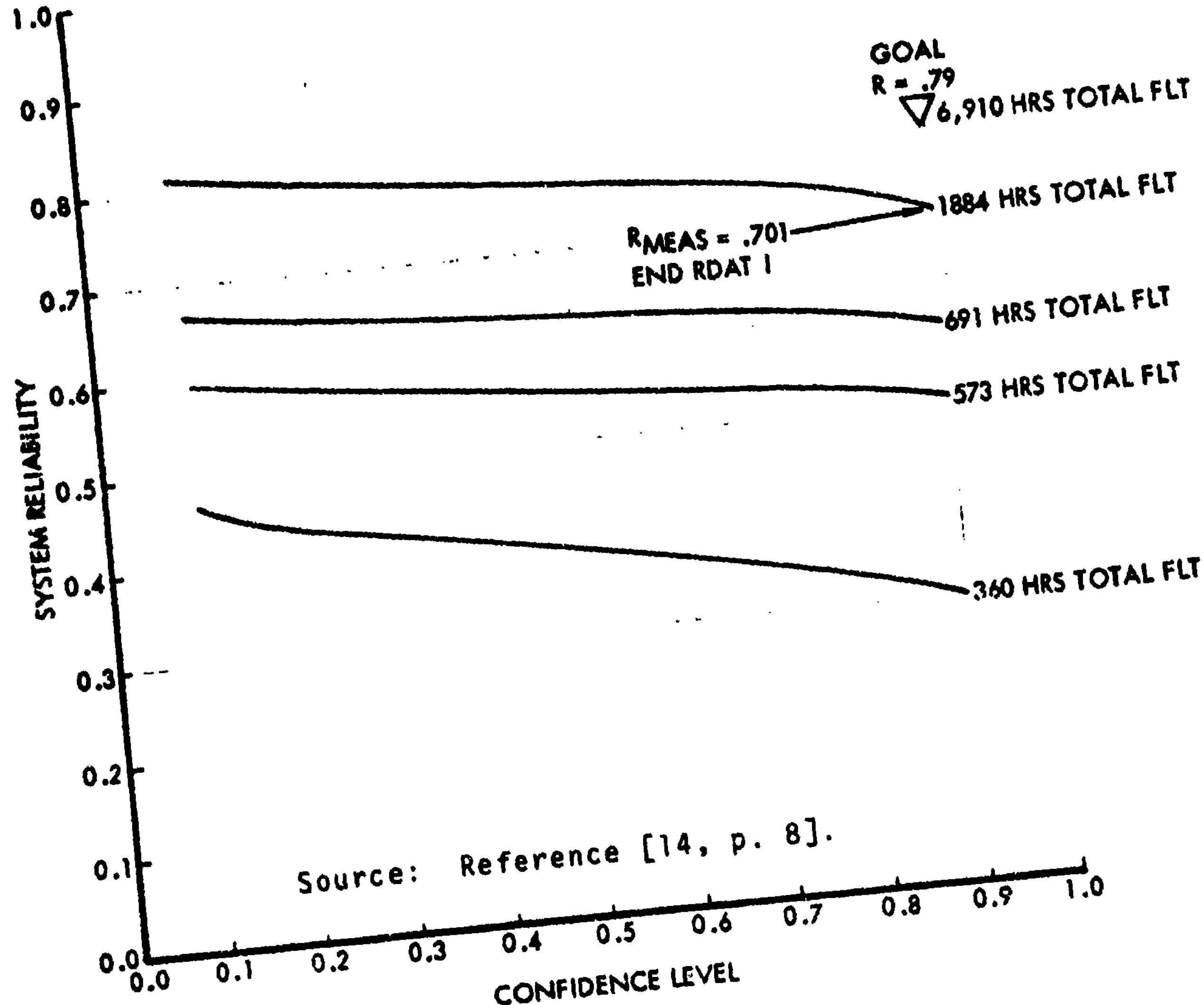


Figure 47. RELIABILITY GROWTH BY TOTAL FLIGHT-HOURS (MISSION RELIABILITY VALUES VERSUS CONFIDENCE LEVEL - GFM AT PAR)

"simulated measurement" of mission reliability. Figure 48 (from [14, Vol. I, p. 81]) shows the results of a sililar Monte Carlo simulation to "measure" system reliab ility. In our opinion, the results of Lockheed's computations are wildly optimistic.



Source: Reference [14, p. 8].

Figure 48. RELIABILITY GROWTH BY TOTAL FLIGHT-HOURS (SYSTEM RELIABILITY VALUES VERSUS CONFIDENCE LEVEL - GFM AT PAR)

3. Data Analysis by IDA

The statistical analysis we have performed is an attempt to measure any reliability improvement (or degradation) that occurred in the AH-56A during the period of flight testing (September 1967 through December 1971). The approach we have used is to model the occurrences of failures by means of a

Non-Homogeneous Poisson Process (NHPP) having a mean value function m(t)--i.e., m(t) = expected number of failures in the internal [0,t]--of the form

$$m(t) = \lambda t^{\beta} , \tag{1}$$

where λ and β[1] are positive constants, which must be estimated from the data. (See Donelson [15] for a complete discussion of these statistical methods.) The instantaneous failure rate r(t) is given by the time derivative of Equation (1) and has the form

$$r(t) = \lambda\beta t^{\beta-1} . \tag{2}$$

Thus, if $0 < \beta < 1$, the instantaneous failure rate of the system is decreasing in time and the system is undergoing "reliability growth." The expected cumulative failure rate c(t)--i.e., c(t) = expected number of failures in [0,t]/t--therefore has the form

$$c(t) = \frac{m(t)}{t} . \tag{3}$$

Substituting Equation (1) into Equation (3), we obtain

$$c(t) = \lambda t^{\beta-1} \tag{4}$$

for the expected cumulative failure rate. When c(t) given by Equation (4) is plotted versus t on full logarithmic paper, the result is a straight line having slope $(\beta-1)$ and intercept λ at $t = 1$. If $0 < \beta < 1$, the slope is negative--indicating that the expected cumulative failure rate is decreasing in time.

Our analysis of the AH-56A reliability data has been performed for the total system and for each mode (subsystem) listed in the first paragraph of this chapter. For each mode

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[1] $1-\beta$ corresponds to the α used in Duane's and General Electric's RPM reliability-growth models.

we have established the trend of cumulative failure-rate (= cumulative failures ÷ cumulative flight-hours) versus cumulative flight-hours. We use maximum-likelihood estimation to estimate λ and β in Equations (1), (2), and (4). Having these estimates of λ and β, we then estimate mean time between failures (MTBF), τ, and reliability for a 2.5-hour mission, R(2.5), using the formulas

$$\tau_n = \left(\frac{1}{\beta}\right)\left(\frac{1}{\lambda}\right)^{\frac{1}{\beta}}\left(\frac{\Gamma\left(\frac{1}{\beta}+n-1\right)}{\Gamma(n)}\right) \tag{5}$$

and

$$R(2.5) = \int_0^{\infty} \frac{(\lambda t^{\beta})^{n-2}}{(n-2)!} (\lambda\beta t^{\beta-1}) \exp\left[-\lambda(2.5+t)^{\beta}\right] dt\ , \tag{6}$$

where n denotes the cumulative number of failures at the time the estimate is made. $\Gamma(\cdot)$ is the gamma function and $\Gamma(n) = (n-1)!$ for n = 1, 2, ... (see Donelson [15] for a derivation of Equations (5) and (6)).

Some qualifications on the limits of our analysis need to be pointed out. First, from the data given by Lockheed [14], it is very difficult to determine whether a failure aborted a test flight (or would abort a 2.5-hour mission). The data in Volume III of Reference [14] contain codes that indicate only where a failure was observed (either in flight or on the ground). Also, in the time allotted to this study, it was not possible to pinpoint those components on the AH-56A that are essential to the long-endurance 2.5-hour mission. Second, by examining the failure data, it is difficult to determine whether a failure would require unscheduled maintenance. Since not all the failures reported by Lockheed would necessarily abort a mission, it is not possible for us to estimate mission reliability. However, 1,541 of the 1,553 failures that we have included in our data in Table 22 are chargeable

under the definitions given in Paragraph 7.4.4.3 (Appendix A, below). Of the remaining (1,553-1,541 =) 12 failures, seven were induced failures, two were "open--not yet classified," and three were secondary-dependent failures. Therefore, we feel that our estimates of MTBF (see below) are reasonable estimates of the mean time between chargeable failures. Accordingly, our reliability estimates given by Equation (6) represent the probability of completing a 2.5-hour mission without incurring a chargeable failure.

a. Total System

Table 22 contains the monthly failure count and monthly cumulative failure total for the total AH-56A system. The cumulative failures in a given month are divided by the cumulative flight-hours from Table 21 for the corresponding month, to obtain the cumulative failure rate for each month of flight testing from September 1967 to December 1971. The cumulative failure rate for the total AH-56A system is tabulated in Table 22. Figure 49 shows a full logarithmic plot of cumulative failure rate versus cumulative flight-hours for the data from Table 22. The maximum-likelihood estimates of λ and β in Equations (1) and (4) for the data from Table 22 are

$$\hat{\lambda} = 3.384 \quad \text{and} \quad \hat{\beta} = 0.844 \ .$$

The dashed line in Figure 49 is a plot of Equation (4) for these values of λ and β. It represents the maximum-likelihood estimate of the expected cumulative failure-rate function. The slope of this line is

$$\hat{\beta} - 1 = 0.844 - 1 = -0.156 \ .$$

The negative slope of the dashed line in Figure 49 is indicative of overall reliability improvement in the AH-56A during the 52-month flight-test program. The estimated MTBF of the AH-56A system after 1,426 hours of flight testing is

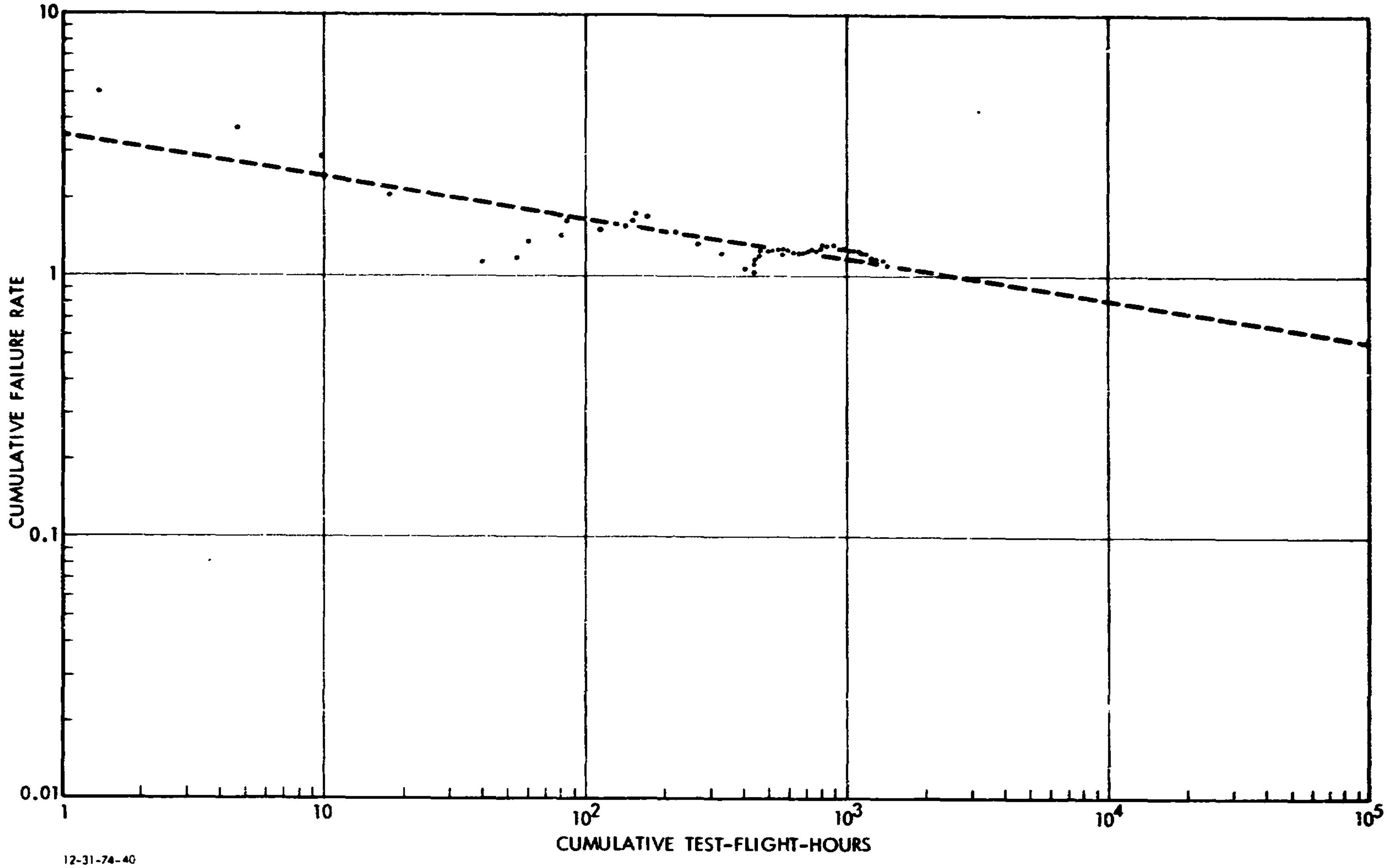

Figure 49. AH-56A RELIABILITY GROWTH CURVE FOR TOTAL SYSTEM

$$\tau = 1.09 \text{ hours} .$$

The estimated reliability for a 2.5-hour mission is

$$R(2.5) = 0.100 .$$

This number represents the estimated probability that the AH-56A will complete a 2.5-hour mission without incurring a chargeable failure; the corresponding Lockheed estimate is 0.701 at a 90-percent confidence level (see Figure 48, above).

b. Airframe Components (Mode 1a)

Table 23 contains the monthly failure count and monthly cumulative failure rate for the airframe components of the AH-56A. (See the beginning of this chapter for the subsystems included in Mode 1a.) Figure 50 shows the reliability growth curve for the airframe components. It shows cumulative failure rate plotted versus cumulative flight-hours. The dashed line in Figure 50 represents the maximum-likelihood estimate of the expected cumulative failure rate under the hypothesis of Equations (1) and (4). The maximum-likelihood estimates of λ and β in this case are

$$\hat{\lambda} = 2.673 \quad \text{and} \quad \hat{\beta} = 0.711 .$$

The slope of the growth curve is, therefore,

$$\hat{\beta} - 1 = 0.711 - 1 = -0.289 ,$$

which indicates reliability improvement. We note that, after the first 100 flight-hours, the points in Figure 50 lie very close to the straight line. The MTBF for these components is estimated at $\tau = 4.29$ hours, while the estimated reliability for a 2.5-hour mission is $R(2.5) = 0.558$.

Table 23. MONTHLY AND CUMULATIVE FAILURES (WITH CUMULATIVE RATE) FOR THE AH-56A (CHEYENNE) AIRFRAME COMPONENTS (MODE 1a)

Monthly Failures		Cumulative Failures		Monthly Failures		Cumulative Failures	
Month	Number	Number	Rate	Month	Number	Number	Rate
9/67	2	2	1.429	11/69	7	270	0.504
10/67	1	3	0.638	12/69	7	277	0.493
11/67	5	8	0.816	1/70	2	279	0.491
12/67	2	10	0.556	2/70	4	283	0.480
1/68	4	14	0.348	3/70	1	284	0.459
2/68	10	24	0.441	4/70	2	286	0.435
3/68	6	30	0.501	5/70	5	291	0.426
4/68	18	48	0.596	6/70	6	297	0.419
5/68	9	57	0.679	7/70	6	303	0.419
6/68	14	71	0.629	8/70	9	312	0.414
7/68	20	91	0.645	9/70	6	318	0.405
8/68	13	104	0.686	10/70	18	336	0.419
9/68	11	115	0.739	11/70	5	341	0.409
10/68	13	128	0.742	12/70	20	361	0.410
11/68	16	144	0.657	1/71	9	370	0.398
12/68	14	158	0.590	2/71	7	377	0.394
1/69	25	183	0.556	3/71	17	394	0.402
2/69	8	191	0.469	4/71	4	398	0.388
3/69	8	199	0.450	5/71	6	404	0.385
4/69	3	202	0.457	6/71	4	408	0.374
5/69	10	212	0.478	7/71	6	414	0.367
6/69	11	223	0.498	8/71	12	426	0.366
7/69	10	233	0.509	9/71	10	436	0.355
8/69	5	238	0.512	10/71	7	443	0.346
9/69	8	246	0.496	11/71	16	459	0.339
10/69	17	263	0.503	12/71	8	467	0.327

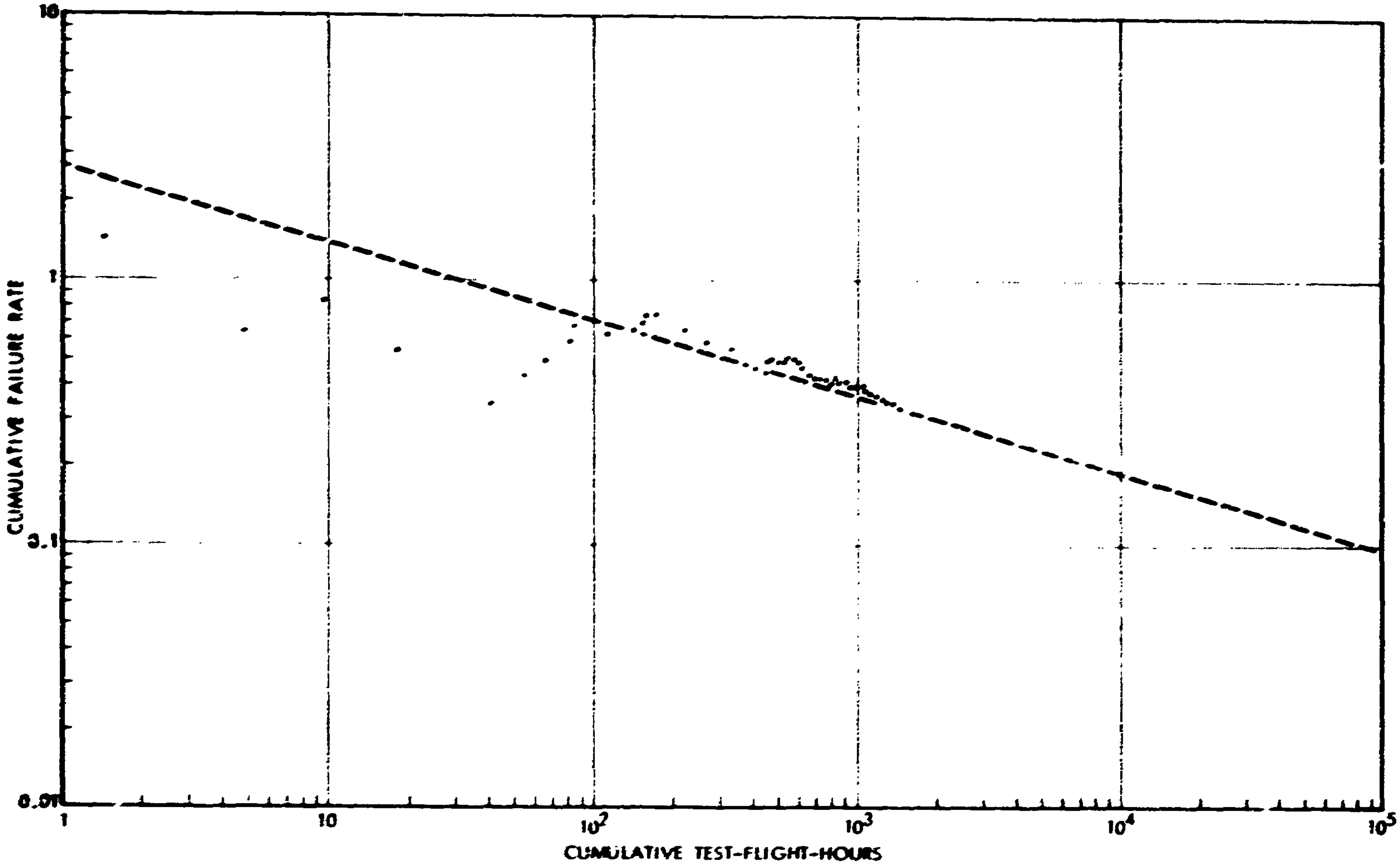

Figure 50. AH-56A RELIABILITY GROWTH CURVE FOR AIRFRAME COMPONENTS (MODE 1a)

c. Rotors and Propellers (Mode 1b)

Table 24 contains the monthly failure count and monthly cumulative failure rate for the subsystems included in Mode 1b. This mode includes the AH-56A main rotor, antitorque rotor, and tail-pusher propeller. The reliability-growth curve for these components is shown in Figure 51. The maximum-likelihood estimate of λ and β for this case are

$$\hat{\lambda} = 0.784 \quad \text{and} \quad \hat{\beta} = 0.672 .$$

The expected cumulative failure-rate curve given by the dashed line in Figure 51 has slope -0.328. The estimated MTBF for the components in Mode 1b is

$$\tau = 20.5 \text{ hours} ,$$

and the estimated reliability for a 2.5-hour mission is

$$R(2.5) = 0.884 .$$

We note that the data points for this mode lie very close to the expected value curve after 300 flight-hours. Also, the components in Mode 1b experienced the most rapid reliability improvement (apart from the XM-53 7.62-mm Machine-Gun System, which is covered in Section B of this chapter, below) of any subgroup of AH-56A components, in the sense that the slope of the expected cumulative failure-rate curve for Mode-1b components is less (i.e., steeper) than the corresponding slopes for the other categories.

d. Gear Boxes and Drives (Mode 1c)

This mode includes the main transmission, transmission lube system, torque meter shaft, tail rotor shafting, and the APU shaft and gearbox. Table 25 contains the monthly failure count and monthly cumulative failure rate for the Mode-1c components. The cumulative failure rate from Table 25 is plotted versus cumulative flight-hours in Figure 52. The maximum-likelihood

Table 24. MONTHLY AND CUMULATIVE FAILURES (WITH CUMULATIVE RATE) FOR THE AH-56A (CHEYENNE) ROTORS AND PROPELLERS (MODE 1b)

Monthly Failures		Cumulative Failures		Monthly Failures		Cumulative Failures	
Month	Number	Number	Rate	Month	Number	Number	Rate
9/67	1	1	0.714	11/69	2	58	0.108
10/67	1	2	0.426	12/69	0	58	0.103
11/67	0	2	0.204	1/70	1	59	0.104
12/67	3	5	0.278	2/70	0	59	0.100
1/68	0	5	0.124	3/70	0	59	0.095
2/68	1	6	0.110	4/70	0	59	0.090
3/68	3	9	0.150	5/70	0	59	0.086
4/68	3	12	0.149	6/70	1	60	0.085
5/68	4	16	0.191	7/70	1	61	0.084
6/68	5	21	0.186	8/70	1	62	0.082
7/68	7	28	0.198	9/70	6	68	0.087
8/68	4	32	0.211	10/70	0	68	0.085
9/68	4	36	0.231	11/70	1	69	0.083
10/68	0	36	0.209	12/70	2	71	0.081
11/68	1	37	0.169	1/71	0	71	0.076
12/68	1	38	0.142	2/71	0	71	0.074
1/69	3	41	0.125	3/71	6	77	0.079
2/69	2	43	0.106	4/71	4	81	0.079
3/69	3	46	0.104	5/71	1	82	0.078
4/69	0	46	0.104	6/71	0	82	0.075
5/69	1	47	0.106	7/71	2	84	0.074
6/69	0	47	0.105	8/71	3	87	0.075
7/69	0	47	0.103	9/71	3	90	0.073
8/69	1	48	0.103	10/71	6	96	0.075
9/69	5	53	0.107	11/71	5	101	0.075
10/69	3	56	0.107	12/71	2	103	0.072

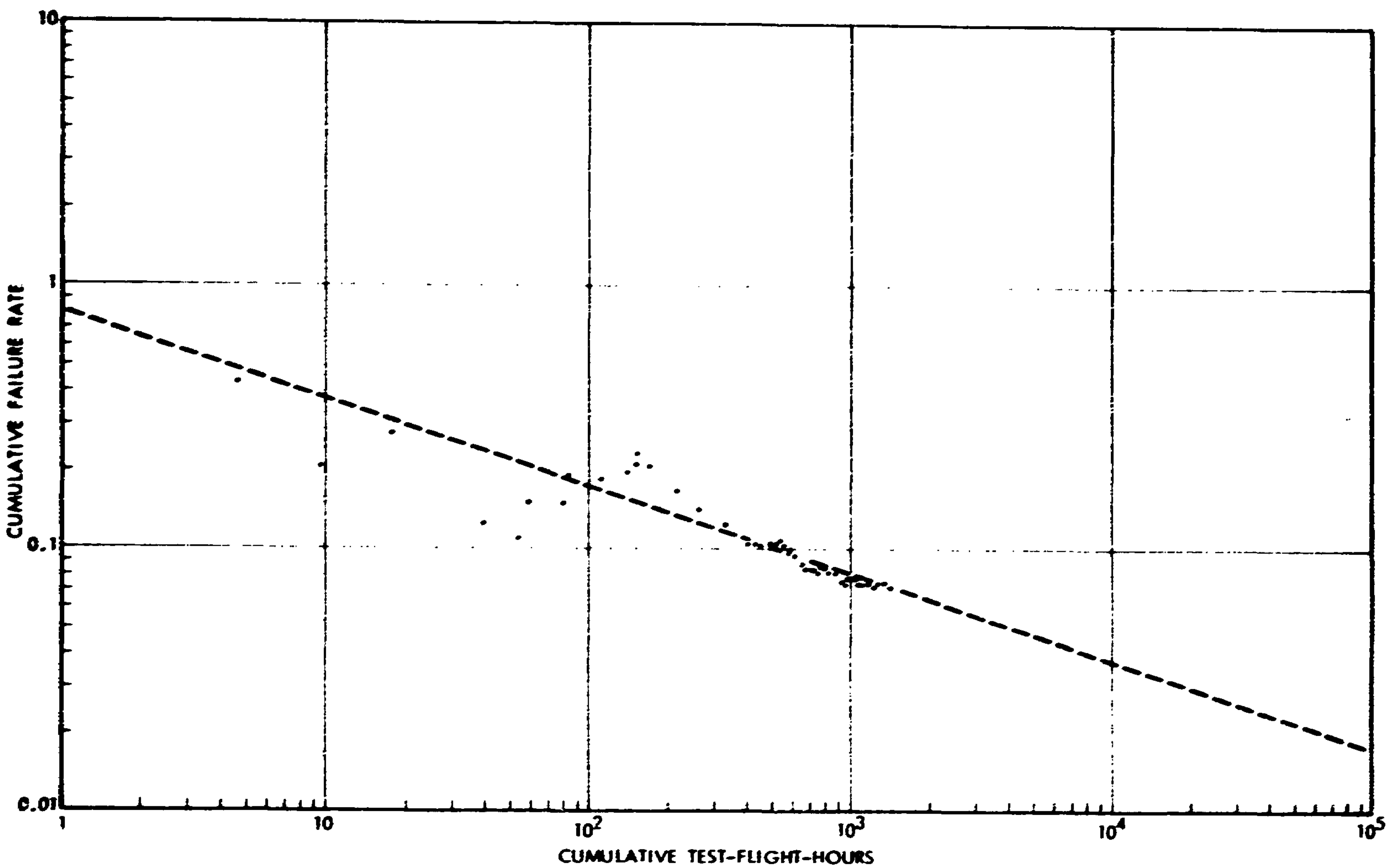

Figure 51. AH-56A RELIABILITY GROWTH CURVE FOR ROTORS AND PROPELLERS (MODE 1b)

Table 25. MONTHLY AND CUMULATIVE FAILURES (WITH CUMULATIVE RATE) FOR THE AH-56A (CHEYENNE) GEAR BOXES AND DRIVES (MODE 1c)

Monthly Failures		Cumulative Failures		Monthly Failures		Cumulative Failures	
Month	Number	Number	Rate	Month	Number	Number	Rate
9/67	0	0	0.000	11/69	1	75	0.140
10/67	1	1	0.213	12/69	1	76	0.135
11/67	0	1	0.102	1/70	2	78	0.137
12/67	1	2	0.111	2/70	3	81	0.137
1/68	1	3	0.075	3/70	0	81	0.131
2/68	2	5	0.092	4/70	4	85	0.129
3/68	2	7	0.117	5/70	0	85	0.124
4/68	6	13	0.161	6/70	2	87	0.123
5/68	4	17	0.203	7/70	0	87	0.120
6/68	3	20	0.177	8/70	3	90	0.119
7/68	6	26	0.184	9/70	5	95	0.121
8/68	2	28	0.185	10/70	7	102	0.127
9/68	3	31	0.199	11/70	7	109	0.131
10/68	2	33	0.191	12/70	10	119	0.135
11/68	8	41	0.187	1/71	4	123	0.132
12/68	2	43	0.161	2/71	2	125	0.130
1/69	3	46	0.140	3/71	4	129	0.132
2/69	5	51	0.125	4/71	3	132	0.129
3/69	1	52	0.118	5/71	1	133	0.127
4/69	3	55	0.124	6/71	3	136	0.125
5/69	1	56	0.126	7/71	0	136	0.121
6/69	2	58	0.129	8/71	1	137	0.118
7/69	4	62	0.135	9/71	1	138	0.112
8/69	5	67	0.144	10/71	2	140	0.109
9/69	3	70	0.141	11/71	1	141	0.104
10/69	4	74	0.141	12/71	0	141	0.099

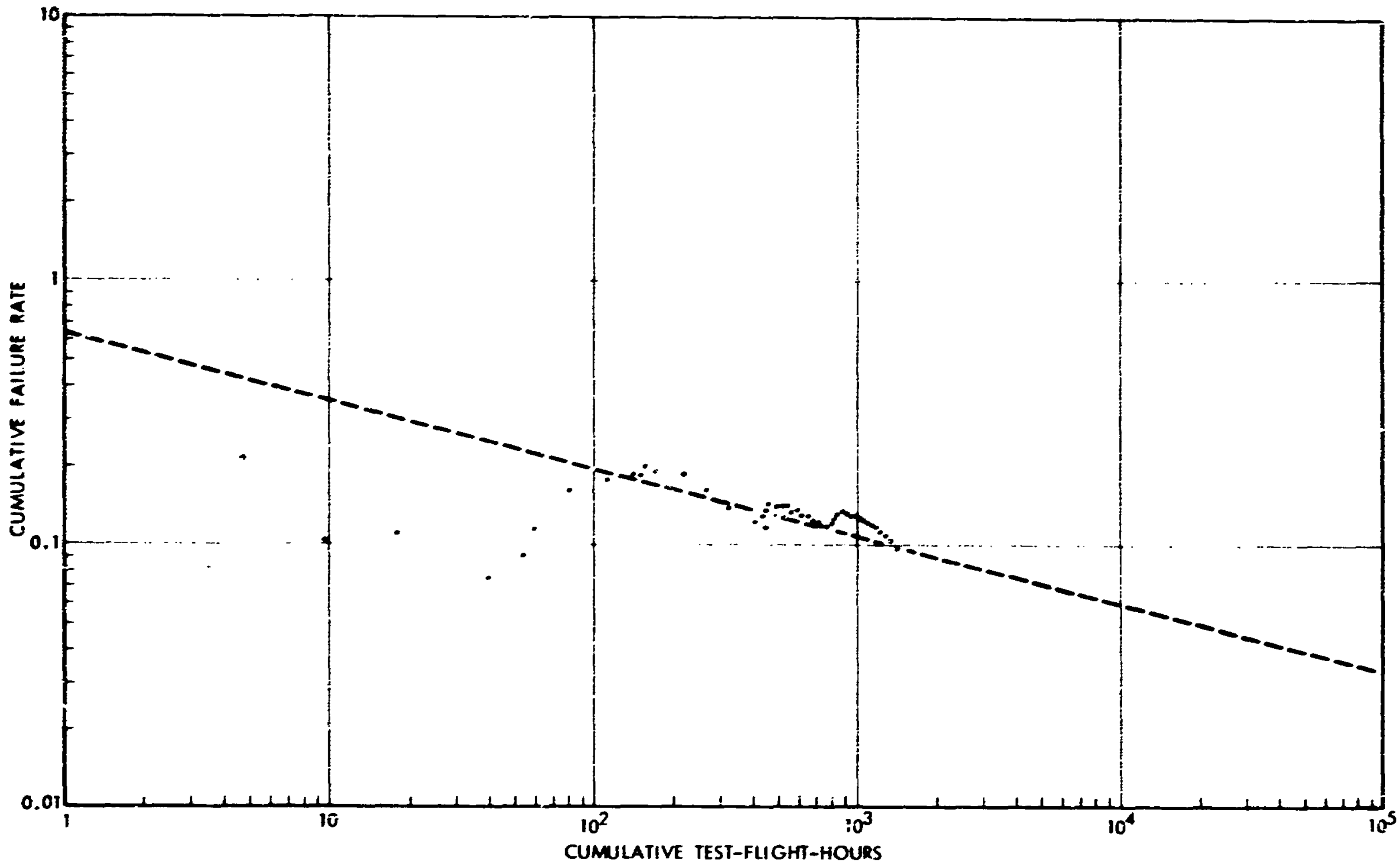

Figure 52. AH-56A RELIABILITY GROWTH CURVE FOR GEAR BOXES AND DRIVES (MODE 1c)

estimates of λ and β for the Mode-1c components are

$$\hat{\lambda} = 0.624 \quad \text{and} \quad \hat{\beta} = 0.746 \ .$$

The slope of the expected cumulative failure-rate curve in this case is -0.254. The estimated MTBF for the Mode-1c component is

$$\tau = 13.59 \text{ hours} \ ,$$

and the estimated reliability of these components for a 2.5-hour mission is

$$R(2.5) = 0.831 \ .$$

e. <u>Power Plant (Mode 1d)</u>

This category includes the main engines, engine accessories, engine starting system, engine power and speed-control system, engine oil supply, and auxiliary power unit (APU). Table 26 contains the monthly failure count and monthly cumulative failure rate for the Mode-1d components. In Figure 53, the cumulative failure rate for these components is plotted versus cumulative flight-hours. The maximum-likelihood estimates of λ and β for the Mode-1d components are

$$\hat{\lambda} = 0.278 \quad \text{and} \quad \hat{\beta} = 0.881 \ .$$

The dashed line in Figure 53 represents the expected cumulative failure-rate curve for Mode-1d components and has slope -0.119 (i.e., $\hat{\beta} - 1 = 0.881 - 1 = -0.119$). The estimated MTBF for these components is

$$\tau = 9.69 \text{ hours} \ ,$$

and their estimated reliability for a 2.5-hour mission is

$$R(2.5) = 0.772 \ .$$

Table 26. MONTHLY AND CUMULATIVE FAILURES (WITH CUMULATIVE RATE) FOR THE AH-56A (CHEYENNE) POWER PLANTS (MODE 1d)

Monthly Failures		Cumulative Failures		Monthly Failures		Cumulative Failures	
Month	Number	Number	Rate	Month	Number	Number	Rate
9/67	0	0	0.000	11/69	2	74	0.138
10/67	0	0	0.000	12/69	0	74	0.132
11/67	1	1	0.102	1/70	4	78	0.137
12/67	0	1	0.056	2/70	4	82	0.139
1/68	0	1	0.025	3/70	3	85	0.138
2/68	1	2	0.037	4/70	9	94	0.143
3/68	1	3	0.050	5/70	7	101	0.148
4/68	6	9	0.112	6/70	6	107	0.151
5/68	2	11	0.131	7/70	6	113	0.156
6/68	3	14	0.124	8/70	5	118	0.157
7/68	5	19	0.135	9/70	6	124	0.158
8/68	3	22	0.145	10/70	4	128	0.159
9/68	1	23	0.148	11/70	3	131	0.157
10/68	2	25	0.145	12/70	8	139	0.158
11/68	3	28	0.128	1/71	2	141	0.152
12/68	7	35	0.131	2/71	6	147	0.153
1/69	5	40	0.122	3/71	1	148	0.151
2/69	7	47	0.115	4/71	6	154	0.150
3/69	4	51	0.115	5/71	1	155	0.148
4/69	0	51	0.115	6/71	0	155	0.142
5/69	3	54	0.122	7/71	1	156	0.138
6/69	6	60	0.134	8/71	1	157	0.135
7/69	2	62	0.135	9/71	4	161	0.131
8/69	6	68	0.146	10/71	5	166	0.130
9/69	3	71	0.143	11/71	0	166	0.123
10/69	1	72	0.138	12/71	1	167	0.117

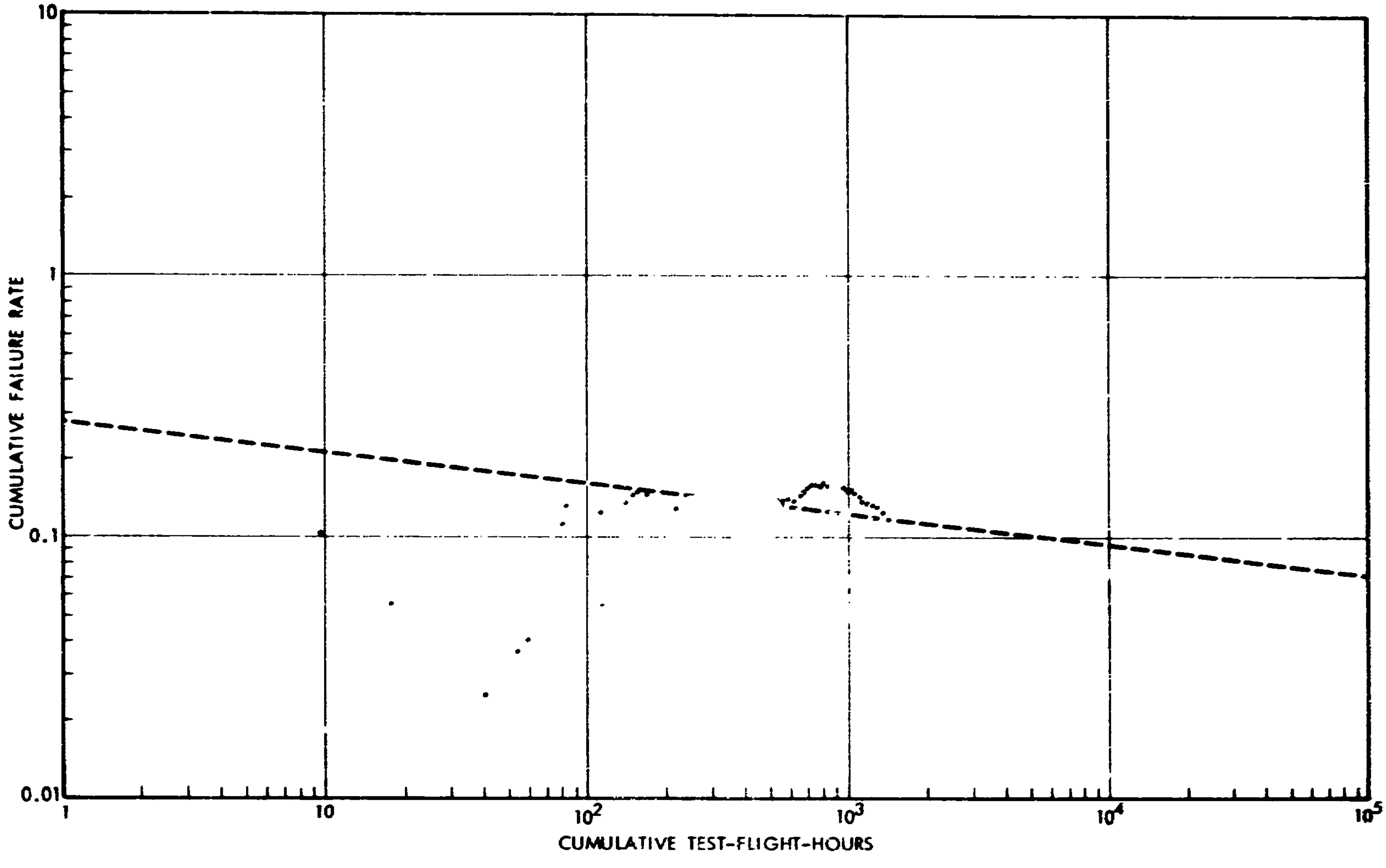

Figure 53. AH-56A RELIABILITY GROWTH CURVE FOR POWER PLANT (MODE 1d)

f. Instruments (Mode 2)

The components included in this mode are listed at the beginning of this chapter. Table 27 contains the monthly failure count and the monthly cumulative failure rate for the Mode-2 components. The cumulative failure rate from Table 27 is plotted versus cumulative flight-hours in Figure 54. The maximum-likelihood estimates of λ and β for the Mode-2 components are

$$\hat{\lambda} = 1.253 \quad \text{and} \quad \hat{\beta} = 0.738 .$$

The slope of the expected cumulative failure-rate curve (given by the dashed line in Figure 54 is -0.262--indicating a moderately rapid rate of reliability improvement. The estimate of MTBF for Mode-2 components is

$$\tau = 7.24 \text{ hours} ,$$

and their estimated reliability for a 2.5-hour mission is

$$R(2.5) = 0.708 .$$

g. Communications (Mode 3)

Table 28 contains the monthly failure count and monthly cumulative failure rate for the AH-56A communications system. The reliability-growth curve for these components is shown in Figure 55, where the cumulative failure rate from Table 28 is plotted versus cumulative flight-hours. The maximum-likelihood estimates of λ and β for these components are

$$\hat{\lambda} = 0.121 \quad \text{and} \quad \hat{\beta} = 0.874 .$$

The slope of the dashed line in Figure 55 is -0.126. The estimated MTBF of the AH-56A communications system is

$$\tau = 23.59 \text{ hours} ,$$

and the estimated reliability for these components is

$$R(2.5) = 0.899 .$$

Table 27. MONTHLY AND CUMULATIVE FAILURES (WITH CUMULATIVE RATE) FOR THE AH-56A (CHEYENNE) INSTRUMENTS (MODE 2)

Monthly Failures		Cumulative Failures		Monthly Failures		Cumulative Failures	
Month	Number	Number	Rate	Month	Number	Number	Rate
9/67	3	3	2.143	11/69	1	108	0.202
10/67	7	10	2.128	12/69	4	112	0.199
11/67	5	15	1.531	1/70	3	115	0.202
12/67	3	18	1.000	2/70	8	123	0.208
1/68	1	19	0.473	3/70	4	127	0.205
2/68	3	22	0.404	4/70	5	132	0.201
3/68	4	26	0.434	5/70	7	139	0.203
4/68	1	27	0.335	6/70	11	150	0.212
5/68	2	29	0.346	7/70	6	156	0.216
6/68	6	35	0.310	8/70	8	164	0.218
7/68	6	41	0.291	9/70	16	180	0.229
8/68	4	45	0.297	10/70	1	181	0.225
9/68	2	47	0.302	11/70	12	193	0.231
10/68	4	51	0.296	12/70	17	210	0.239
11/68	6	57	0.260	1/71	9	219	0.236
12/68	7	64	0.239	2/71	5	224	0.234
1/69	3	67	0.204	3/71	3	227	0.231
2/69	12	79	0.194	4/71	2	229	0.223
3/69	4	83	0.188	5/71	9	238	0.227
4/69	1	84	0.190	6/71	7	245	0.225
5/69	3	87	0.196	7/71	2	247	0.219
6/69	1	88	0.196	8/71	3	250	0.215
7/69	2	90	0.197	9/71	5	255	0.208
8/69	8	98	0.211	10/71	3	258	0.201
9/69	2	100	0.201	11/71	3	261	0.193
10/69	7	107	0.204	12/71	5	266	0.187

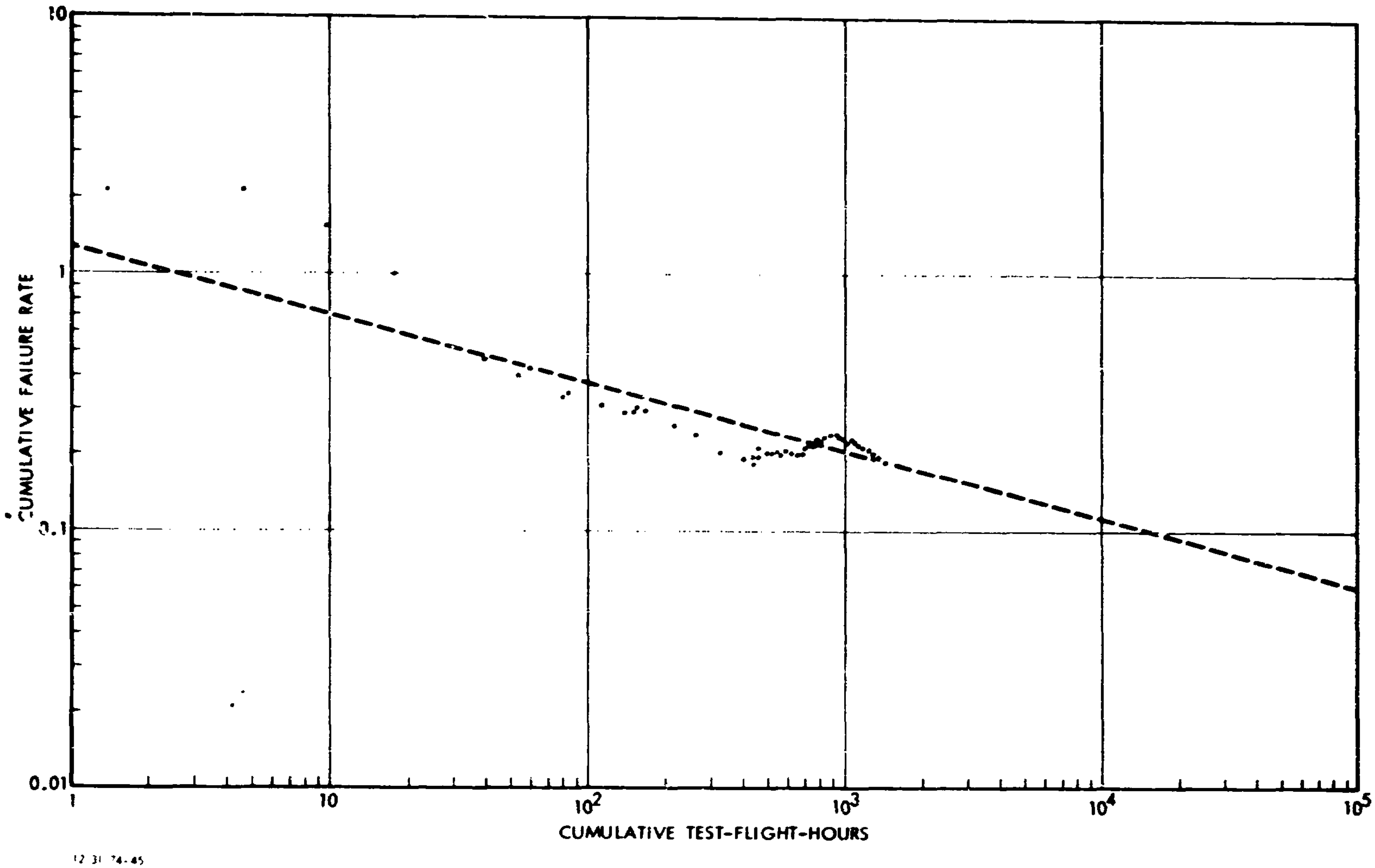

Figure 54. AH-56A RELIABILITY GROWTH CURVE FOR INSTRUMENTS (MODE 2)

Table 28. MONTHLY AND CUMULATIVE FAILURES (WITH CUMULATIVE RATE) FOR THE AH-56A (CHEYENNE) COMMUNICATIONS (MODE 3)

Monthly Failures		Cumulative Failures		Monthly Failures		Cumulative Failures	
Month	Number	Number	Rate	Month	Number	Number	Rate
9/67	0	0	0.0000	11/69	0	31	0.0579
10/67	0	0	0.0000	12/69	0	31	0.0552
11/67	0	0	0.0000	1/70	0	31	0.0545
12/67	0	0	0.0000	2/70	0	31	0.0525
1/68	2	2	0.0498	3/70	0	31	0.0502
2/68	2	4	0.0735	4/70	1	32	0.0487
3/68	1	5	0.0835	5/70	4	36	0.0527
4/68	0	5	0.0621	6/70	1	37	0.0523
5/68	1	6	0.0715	7/70	1	38	0.0526
6/68	0	6	0.0532	8/70	4	42	0.0558
7/68	5	11	0.0780	9/70	1	43	0.0547
8/68	1	12	0.0792	10/70	1	44	0.0548
9/68	3	15	0.0963	11/70	3	47	0.0563
10/68	1	16	0.0923	12/70	1	48	0.0545
11/68	0	16	0.0730	1/71	2	50	0.0538
12/68	1	17	0.0635	2/71	1	51	0.0532
1/69	1	18	0.0547	3/71	3	54	0.0551
2/69	2	20	0.0491	4/71	1	55	0.0536
3/69	0	20	0.0452	5/71	0	55	0.0524
4/69	0	20	0.0452	6/71	2	57	0.0522
5/69	0	20	0.0451	7/71	4	61	0.0541
6/69	0	20	0.0446	8/71	4	65	0.0558
7/69	3	23	0.0502	9/71	1	66	0.0537
8/69	2	25	0.0538	10/71	0	66	0.0515
9/69	4	29	0.0584	11/71	1	67	0.0495
10/69	2	31	0.0592	12/71	2	69	0.0484

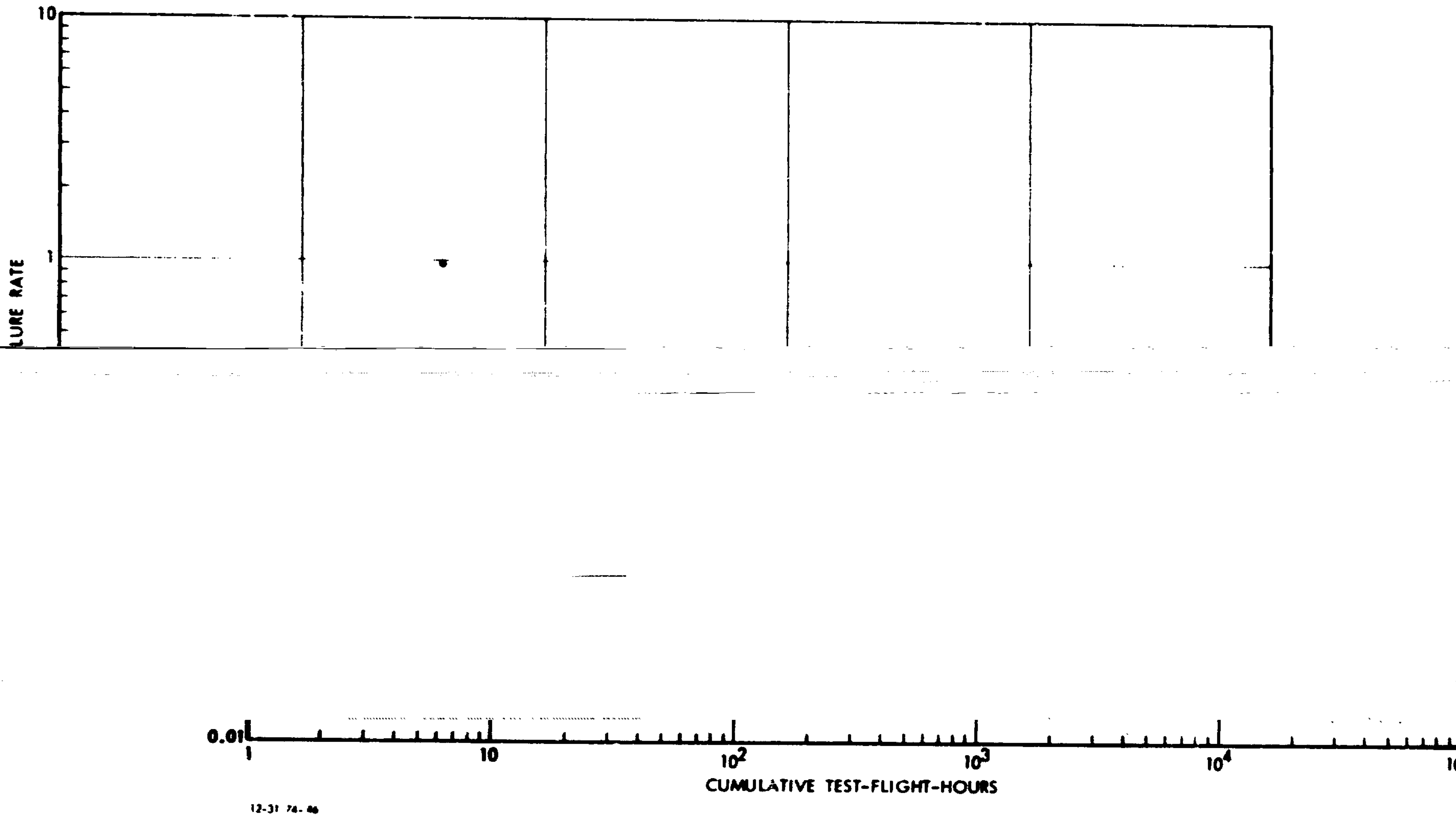

Figure 55. AH-56A RELIABILITY GROWTH CURVE FOR COMMUNICATIONS (MODE 3)

We note that the slope of the reliability-growth curve for the Mode-3 components is about the same as the slope of the reliability-growth curve for the AH-56A power plants (Mode 1d). Both these categories experienced only relatively minor reliability improvement during the 52 months of flight testing on the CHEYENNE.

h. Navigation System (Mode 4)

The components included in this mode are listed at the beginning of this chapter. The navigation system was installed on the AH-56A in January 1969 after a total of 267.6 test-flight-hours had been accumulated. Accordingly, Table 29 shows the monthly failure count and monthly cumulative failure rate for Mode-4 components beginning in January 1969. The cumulative test-hours in Table 29 represent test-flight-hours accumulated on the AH-56A after January 1969. Mode 4 also includes some weapon-systems components that were not flight tested until March 1969.

The monthly cumulative failure rate from Table 29 is plotted versus cumulative flight-test time in Figure 56. We note that the cumulative failure rate for Mode-4 components increases steadily from 0.016 failures per flight-hour in January 1969 to 0.140 failures per flight-hour in October 1970 after 535.2 flight-hours had been accumulated on the Mode-4 components (802.8 flight-hours total on the AH-56A). The maximum-likelihood estimates of λ and β for these components are

$$\hat{\lambda} = 0.043 \quad \text{and} \quad \hat{\beta} = 1.140 \; .$$

The slope of the expected cumulative failure-rate curve in Figure 56 (i.e., the dashed line) is 0.140--indicating an overall increasing trend in cumulative failure rate for Mode-4 components. The estimated MTBF for the Mode-4 components is

$$\tau = 7.58 \text{ hours} \; ,$$

Table 29. MONTHLY AND CUMULATIVE FAILURES (WITH CUMULATIVE FLIGHT-HOURS AND RATE) FOR THE AH-56A (CHEYENNE) NAVIGATION SYSTEM (MODE 4)

Monthly Failures		Flight-Hours		Cumulative Failures	
Month	Number	Monthly	Cumulative	Number	Rate
1/69	1	61.3	61.3	1	0.016
2/69	2	78.6	139.9	3	0.021
3/69	1	34.8	174.7	4	0.023
4/69	0	0.0	174.7	4	0.023
5/69	2	0.9	175.6	6	0.034
6/69	0	4.9	180.5	6	0.033
7/69	4	9.7	190.2	10	0.053
8/69	1	7.0	197.2	11	0.056
9/69	6	31.5	228.7	17	0.074
10/69	1	27.0	255.7	18	0.070
11/69	1	12.3	268.0	19	0.071
12/69	0	26.0	294.0	19	0.065
1/70	2	7.2	301.2	21	0.070
2/70	7	21.2	322.4	28	0.087
3/70	5	28.1	350.5	33	0.094
4/70	8	39.3	389.8	41	0.105
5/70	3	25.7	415.5	44	0.106
6/70	5	25.0	440.5	49	0.111
7/70	6	15.0	455.5	55	0.121
8/70	9	30.2	485.7	64	0.132
9/70	6	32.8	518.5	70	0.135
10/70	5	16.7	535.2	75	0.140
11/70	2	31.8	567.0	77	0.136
12/70	6	45.7	612.7	83	0.135
1/71	6	49.5	662.2	89	0.134
2/71	4	28.2	690.4	93	0.135
3/71	3	22.6	713.0	96	0.135
4/71	5	46.4	759.4	101	0.133
5/71	3	23.5	782.9	104	0.133
6/71	7	40.8	823.7	111	0.135
7/71	5	36.8	860.5	116	0.135
8/71	1	36.9	897.4	117	0.130
9/71	4	63.7	961.1	121	0.126
10/71	2	52.5	1,013.6	123	0.121
11/71	4	72.5	1,086.1	127	0.117
12/71	7	72.3	1,158.4	134	0.116

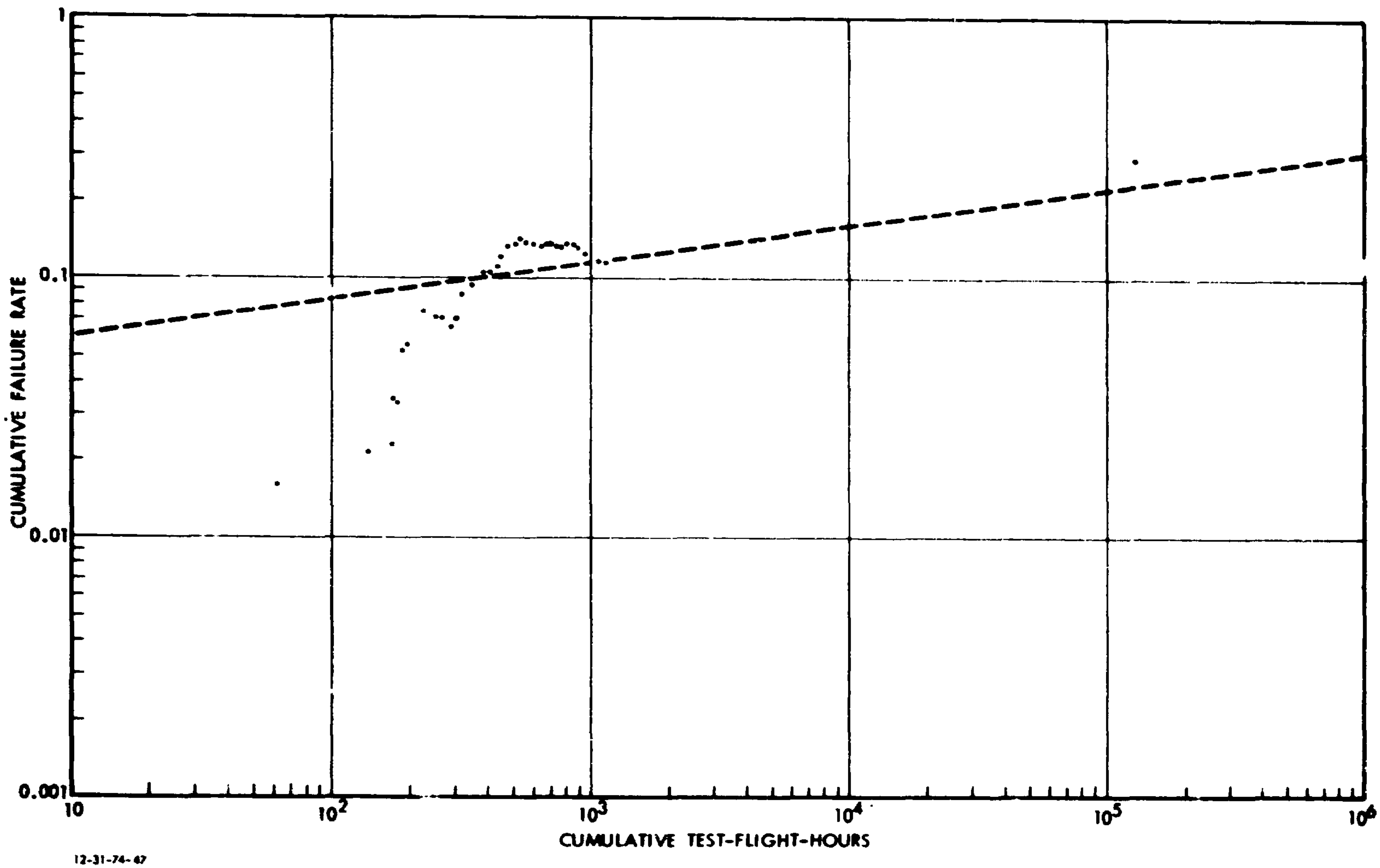

Figure 56. AH-56A RELIABILITY GROWTH CURVE FOR NAVIGATION SYSTEM (MODE 4)

and their estimated reliability for a 2.5-hour mission is

$$R(2.5) = 0.719 .$$

Lacking complete knowledge of the conditions that prevailed during AH-56A flight testing, we are unable to explain the rather sharp increase in the cumulative failure rate and its subsequent leveling off for these components.

i. Computer Central Complex (Mode 5)

The Computer Central Complex (CCC) was installed on the AH-56A for flight testing in March 1969 after 407.5 test-flight-hours had been accumulated on the AH-56A. Accordingly, Table 30 shows the monthly failure totals and monthly cumulative failure rate, beginning in March 1969. The cumulative failure rate is relative to flight-hours accumulated on the AH-56A after February 1969. The cumulative failure rate from Table 30 is plotted versus cumulative flight-hours in Figure 57. The cumulative failure rate for the Mode-5 components decreases from a high of 0.154 failures per flight-hour at 395.3 cumulative test-hours to 0.092 failures per flight-hour at 1,018.5 cumulative test-hours. The maximum-likelihood estimates for λ and β for the data in Table 30 are

$$\hat{\lambda} = 0.233 \quad \text{and} \quad \hat{\beta} = 0.866 .$$

The dashed line in Figure 57 has slope -0.134--indicating that the expected cumulative failure rate for the CCC is decreasing slightly. The estimated MTBF of these components is

$$\tau = 12.5 \text{ hours} ,$$

and their estimated reliability for a 2.5-hour mission is

$$R(2.5) = 0.818 .$$

Table 30. MONTHLY AND CUMULATIVE FAILURES (WITH CUMULATIVE FLIGHT-HOURS AND RATE) FOR THE AH-56A (CHEYENNE) COMPUTER CENTRAL COMPLEX (MODE 5)

Monthly Failures		Flight-Hours		Cumulative Failures	
Month	Number	Monthly	Cumulative	Number	Rate
3/69	1	34.8	34.8	1	0.029
4/69	0	0.0	34.8	0	0.029
5/69	1	0.9	35.7	2	0.056
6/69	0	4.9	40.6	2	0.049
7/69	3	9.7	50.3	5	0.099
8/69	2	7.0	57.3	7	0.122
9/69	1	31.5	88.8	1	0.090
10/69	1	27.0	115.8	9	0.078
11/69	1	12.3	128.1	10	0.078
12/69	2	26.0	154.1	12	0.078
1/70	0	7.2	161.3	12	0.074
2/70	3	21.2	182.5	15	0.082
3/70	6	28.1	210.6	21	0.100
4/70	7	39.3	249.9	28	0.112
5/70	4	25.7	275.6	32	0.116
6/70	8	25.0	300.6	40	0.133
7/70	2	15.0	315.6	42	0.133
8/70	10	30.2	345.8	52	0.150
9/70	6	32.8	378.6	58	0.153
10/70	3	16.7	395.3	61	0.154
11/70	0	31.8	427.1	61	0.143
12/70	0	45.7	472.8	61	0.129
1/71	0	49.5	522.3	61	0.117
2/71	3	28.2	550.5	64	0.116
3/71	1	22.6	573.1	65	0.113
4/71	2	46.4	619.5	67	0.108
5/71	0	23.5	643.0	67	0.104
6/71	4	40.8	683.8	71	0.104
7/71	3	36.8	720.6	74	0.103
8/71	4	36.9	757.5	78	0.103
9/71	7	63.7	821.2	85	0.104
10/71	1	52.5	873.7	86	0.098
11/71	6	72.5	946.2	92	0.097
12/71	2	72.3	1,018.5	94	0.092

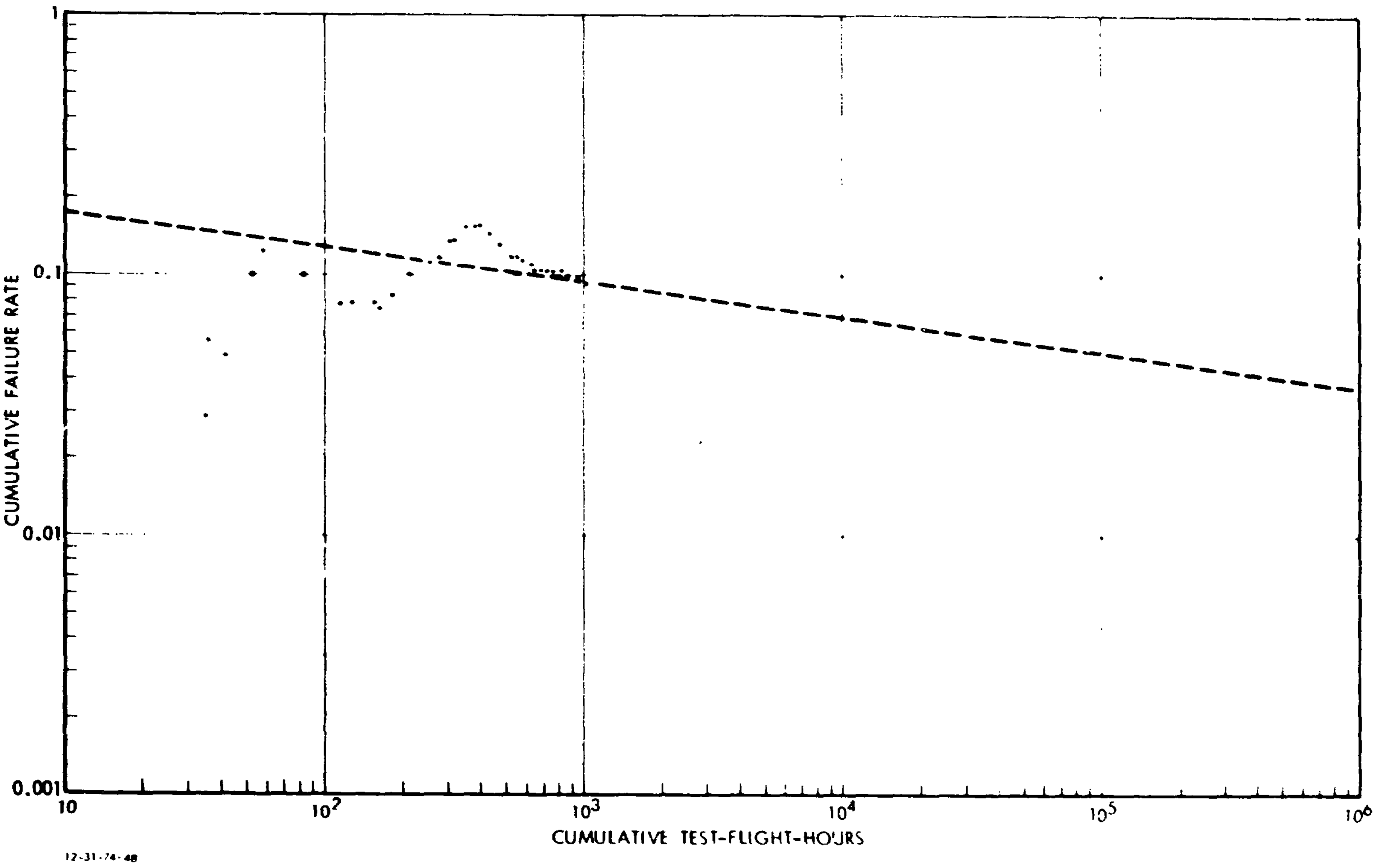

Figure 57. AH-56A RELIABILITY GROWTH CURVE FOR COMPUTER CENTRAL COMPLEX (MODE 5)

j. **Weapon Systems (Mode 6)**

The systems included in this mode are listed at the beginning of this chapter. Flight testing on the weapon systems commenced in March 1969, after the AH-56A had already accumulated 407.5 flight hours. Table 31 contains the monthly failure totals and monthly cumulative failure rate for the Mode-6 failures, starting in March 1969. The cumulative failure rate in Table 31 is relative to flight-hours accumulated on the AH-56A after February 1969. In the following section, we give a more comprehensive reliability-growth analysis for the gun systems using the "Armament Stoppage History" for the XM-51 40-mm Grenade-Launcher System, the XM-52 30-mm Gun System, and the XM-53 7.62-mm Machine-Gun System (tables contained in [14, Vol. I]). The monthly cumulative failure rate from Table 31 is plotted versus cumulative flight-test-hours for these components in Figure 58.

The maximum-likelihood estimates of λ and β for the data from Table 31 are

$$\hat{\lambda} = 0.291 \quad \text{and} \quad \hat{\beta} = 0.848 .$$

The slope of the expected cumulative failure-rate curve in Figure 58 is -0.152--indicating reliability improvement for these components. The estimated MTBF for Mode-6 components is

$$\tau = 11.66 \text{ hours} ,$$

and their estimated reliability for a 2.5-hour mission is

$$R(2.5) = 0.807 .$$

4. **Conclusions**

The analysis presented in this section assumes that failures occur in accordance with a Non-Homogeneous Poisson Process (NHPP), the time parameter of the process being cumulative flight-hours in this case. We further assume that the mean-

Table 31. MONTHLY AND CUMULATIVE FAILURES (WITH CUMULATIVE FLIGHT-HOURS AND RATE) FOR THE AH-56A (CHEYENNE) WEAPON SYSTEMS (MODE 6)

Monthly Failures		Flight-Hours		Cumulative Failures	
Month*	Number	Monthly	Cumulative	Number	Rate
3/69	1	34.8	34.8	1	0.029
4/69	0	0.0	34.8	1	0.029
5/69	1	0.9	35.7	2	0.056
6/69	2	4.9	40.6	4	0.099
7/69	1	9.7	50.3	5	0.099
8/69	6	7.0	57.3	11	0.192
9/69	3	31.5	88.8	14	0.158
10/69	3	27.0	115.8	17	0.147
11/69	3	12.3	128.1	20	0.156
12/69	3	26.0	154.1	23	0.149
1/70	4	7.2	161.3	27	0.167
2/70	3	21.2	182.5	30	0.164
3/70	3	28.1	210.6	33	0.157
4/70	5	39.3	249.9	38	0.152
5/70	2	25.7	275.6	40	0.145
6/70	0	25.0	300.6	40	0.133
7/70	1	15.0	315.6	41	0.130
8/70	3	30.2	345.8	44	0.127
9/70	2	32.8	378.6	46	0.122
10/70	4	16.7	395.3	50	0.126
11/70	3	31.8	427.1	53	0.124
12/70	0	45.7	472.8	53	0.112
1/71	5	49.5	522.3	58	0.111
2/71	2	28.2	550.5	60	0.109
3/71	2	22.6	573.1	62	0.108
4/71	3	46.4	619.5	65	0.105
5/71	2	23.5	643.0	67	0.104
6/71	5	40.8	683.8	72	0.105
7/71	3	36.8	720.6	75	0.104
8/71	7	36.9	757.5	82	0.108
9/71	5	63.7	821.2	87	0.106
10/71	12	52.5	873.7	99	0.113
11/71	3	72.5	946.2	102	0.108
12/71	1	72.3	1,018.5	103	0.101

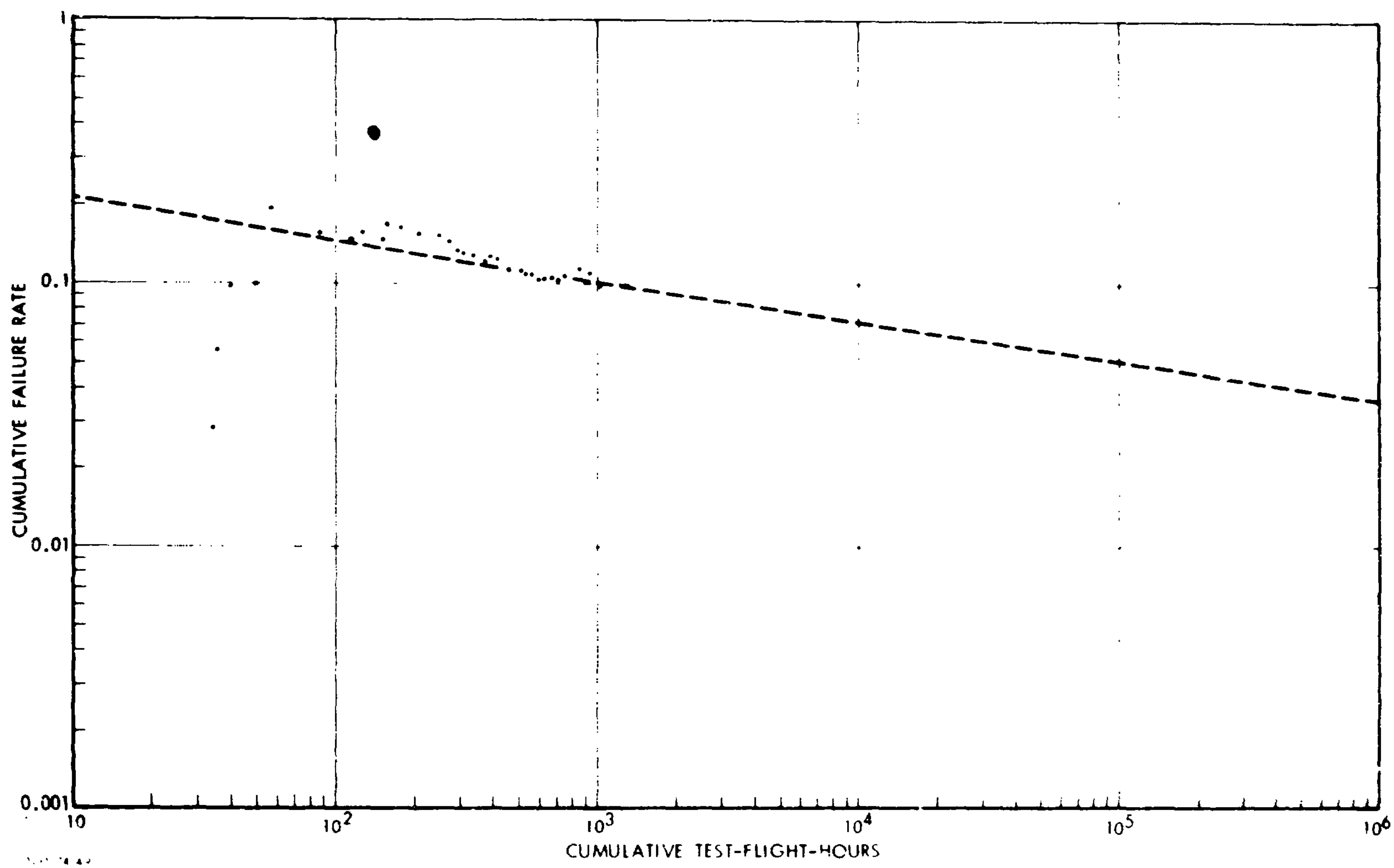

Figure 58. AH-56A RELIABILITY GROWTH CURVE FOR WEAPON SYSTEMS (MODE 6)

value function of this NHPP has the form given by Equation (1). If this assumption is correct, then the expected cumulative failure rate has the form given by Equation (4), which is a straight line on full logarithmic paper. Also, MTBF and reliability (for a 2.5-hour mission) are correctly estimated by Equations (5) and (6), respectively, when the assumptions in Equation (1) are correct. We have used maximum-likelihood estimation to estimate the parameters λ and β appearing in Equations (1) through (6). It is shown in Donelson [15] that this method of estimating λ and β is consistent in the sense that, as the size of the data sample becomes large, the maximum-likelihood estimates of λ and β will be very close to their true values (assuming, of course, that such values exist).

The data presented in this section apply to a program that was terminated in the development stage. (The AH-56A CHEYENNE never went into production.) However, we believe that the data examined here convey several important messages.

First, it is very evident from a quick comparison of our results and the results of Lockheed's computations (Figures 47 and 48) that Lockheed's estimates of AH-56A reliability are much more optimistic than ours. The reasons for these differences are explained, we believe, by the differences in the procedures used to model and estimate the reliability of the AH-56A. Lockheed used a very complicated simulation method, in which the GFM components were assumed to have constant failure rates. Also, Lockheed relied heavily on Paragraph 7.4.4.5, "Deduction of Failures" (see Appendix A, below), to obtain a favorable estimate of AH-56A reliability. Our method examines the statistical pattern in which failures occur in time and estimates MTBF and reliability directly from the data, without assuming any sort of dynamic relationship between the components in which certain components are assumed to have fixed (unchanging) failure rates. Considering the complexity of the AH-56A, we

doubt that a simulation model (which involves hundreds of assumptions) is likely to give meaningful results. On the other hand, our method (which examines the pattern of failure occurrence in time) is able to deduce MTBF and reliability with a minimum number of assumptions.

We see very little justification for deducting a failure for which a fix has reportedly been developed. Of course, it is possible that a fix proposed to correct a failure mode will be entirely effective. But this cannot be ascertained with certainty before the fix is installed and tested. In the case of the AH-56A, many of the fixes that were developed were never installed and tested. The overall effect of Paragraph 7.4.4.5 is to present an overly optimistic picture of the manner in which reliability growth occurred on the AH-56A. To say that 84 percent of the chargeable failures (the percentage of deducted chargeable failures as a percentage of their total) on the AH-56A never occurred is to present a very unrealistic picture of what actually happened. It is our view that all chargeable failures (and perhaps some nonchargeable failures as well) should be counted, for the purpose of measuring reliability growth.

The next important message conveyed by the data presented in this section is that there are simple statistical methods that can be used to monitor reliability improvement effectively and to predict future reliability growth. The cumulative-failure-rate curves shown in Figures 49-54 exhibit considerable statistical regularity. These plots of cumulative failure rate versus cumulative flight-hours show an easily recognizable trend in reliability improvement.

The methods we have employed here to analyze AH-56A reliability improvement do not attempt to explain (1) why failures occur or (2) the dynamics of the failure-causing mechanisms. However, using only the assumption that failures occur in time in accordance with a NHPP, we are able to give a simple mathematical

explanation--Equations (4), (5), and (6)--of the pattern or trend in the occurrence of failures. Measurement of this trend is all that is needed for monitoring reliability improvement. In addition, these methods may be used to forecast cumulative failure rate, MTBF, and reliability. Such forecasts can be monitored for accuracy and can easily be revised and updated.

B. WEAPON SUBSYSTEMS

We have performed a reliability-growth analysis that uses test data from the following weapon systems on the AH-56A (CHEYENNE): XM-51 40-mm Grenade-Launcher System, XM-52 30-mm Gun System, and XM-53 7.62-mm Machine-Gun System.

The source of the data used in this analysis is the AH-56A Armament Stoppage History contained in Reference [14, Vol. I]. This information was collected from logs, monthly test reports, inspection tags, and on-site Design Assurance Representatives. Stoppages were recorded only when the guns failed to fire or point upon command. This condition was recorded for both air firing and ground firing. However, firing from a test installation was not included [14, Vol. I, p. 63].

1. Contractual Reliability Goals and Measurement Procedures

The CHEYENNE contract specified the following reliability goals for each of the weapon systems we have considered:

(1) XM-51 40-mm Grenade-Launcher System (not including the gun or ammunition) 7,150 mean-rounds-to-stoppage (MRTS) after firing 467,000 rounds at 90-percent confidence level.

(2) XM-52 30-mm Gun System (not including the gun or ammunition) 9,550 MRTS after firing 128,000 rounds at 90-percent confidence level.

(3) XM-53 7.62-mm Machine-Gun System (not including the gun or ammunition) 14,400 MRTS after firing 1,056,000 rounds at 90-percent confidence level. [14, Vol. I, pp. xi-xii]

The gun and ammunition are Government Furnished Material (GFM), and their reliability is not included in these reliability goals. Thus, the goals apply only to weapon subsystems such as the turret, feed chute, and control systems.

Procedures that were used by Lockheed to determine the failure count and to measure reliability of the weapon subsystems on the AH-56A may be found in Appendix A, below (Paragraphs 7.4.6 through 7.4.6.6). As we shall demonstrate, Paragraphs 7.4.4.5 (Deduction of Failures) and 7.4.6.6 (Data Acquisition and Evaluation Process) permit the contractor (Lockheed Aircraft Corporation) to estimate AH-56A weapon-systems reliability in an extremely optimistic manner.

2. Data Analysis

a. XM-51 40-mm Grenade-Launcher System

Testing on this system began in September 1968 and continued until 21 December 1971. The data used in our analysis are the Armament Stoppage History for the XM-51 (Ref. [14, Vol. I, pp. 68-103]). During more than three years of testing on the XM-51 40-mm Grenade-Launcher System, Lockheed fired a total of 40,530 rounds (or 8.7 percent of the programmed 467,000 rounds) and reported a total of 166 stoppages, of which 71 were due to Contractor Furnished Material (CFM). However, after deducting failures for which fixes had been developed (in accordance with Paragraph 7.4.4.5, Deduction of Failures) and nonchargeable failures, Lockheed reported a net total of only 14 chargeable failures. It is to be noted that in many cases the fixes (which allowed the deduction of failures) were never incorporated into the weapon system and tested. Thus, using the criteria of Paragraph 7.4.6.6 (above), Lockheed estimated the reliability of the XM-51 as 2,895 MRTS--i.e., 40,530/14 = 2,895 [14, Vol. I, p. xii]).

However, an analysis of Lockheed's data (not counting failures due to GFM) shows that the average firing period without a failure was only 785 rounds, with a standard deviation of 1,063 rounds. Of a total of 50 stoppages due to CFM for which there are rounds-since-last-stoppage data available, in only three of these firing periods did the rounds since last stoppage exceed 2,895 rounds. Thus, Lockheed's estimate of MRTS for the XM-51 lies above the 90th percentile of the data on rounds since last stoppage due to CFM. The deduction of failures for which a fix is developed, even before the fix is incorporated and tested, necessarily includes the optimistic assumptions that the fix will entirely eliminate the failure mode being fixed and will not introduce any new failure modes into the system.

In this study we were primarily interested in the reliability improvement of the entire weapon system, including the gun and ammunition. It is our view that all failures should be counted, for the purpose of measuring reliability growth during a test and development program. Therefore, in our analysis we have counted all failures, whether they are due to CFM or GFM; and we have not deducted any failure for which a fix had reportedly been developed. Table 32 shows a summary of the stoppage history on the XM-51. It is to be noted that our data differ from the data reported by Lockheed. There are two reasons for this. First, there are arithmetic and typographical errors in the data Lockheed reported in Reference [14, Vol. I, pp. 68-103]. In some cases we made the obvious correction, and in others we found it necessary to guess (by splitting the differences). Second, in some instances Lockheed reported weapons stoppages without reporting rounds fired since last stoppage or cumulative rounds fired. We were unable to determine whether these data represent multiple failures detected at the time a weapons stoppage occurred or whether they represent stoppages for which the data were lost.

Table 32. STOPPAGE HISTORY AND CUMULATIVE STOPPAGE RATE FOR THE XM-51 40-mm GRENADE-LAUNCHER SYSTEM

Stoppage Number	Rounds Since Last Stoppage	Cumulative Rounds Fired	Cumulative Stoppage Rate	Stoppage Number	Rounds Since Last Stoppage	Cumulative Rounds Fired	Cumulative Stoppage Rate
1	17	17	0.05880	41	379	11,756	0.00349
2	1	18	0.11110	42	131	11,887	0.00353
3	78	96	0.03130	43	145	12,032	0.00357
4	129	225	0.01780	44	9	12,041	0.00365
5	19	244	0.02050	45	178	12,219	0.00368
6	28	272	0.02210	46	38	12,257	0.00375
7	26	298	0.02350	47	5	12,262	0.00383
8	2	300	0.02670	48	1,669	13,931	0.00345
9	2	302	0.02980	49	1,177	15,108	0.00324
10	7	309	0.03240	50	136	15,244	0.00328
11	142	451	0.02440	51	126	15,370	0.00332
12	184	635	0.01890	52	626	15,996	0.00325
13	185	820	0.01590	53	851	16,847	0.00315
14	185	1,005	0.01390	54	374	17,221	0.00314
15	673	1,678	0.00894	55	28	17,249	0.00319
16	673	2,351	0.00681	56	104	17,353	0.00323
17	673	3,024	0.00562	57	2	17,355	0.00328
18	673	3,697	0.00487	58	307	17,662	0.00328
19	674	4,371	0.00435	59	51	17,713	0.00333
20	778	5,149	0.00388	60	101	17,814	0.00337
21	778	5,927	0.00354	61	180	17,994	0.00339
22	778	6,705	0.00328	62	498	18,492	0.00335
23	957	7,662	0.00300	63	118	18,610	0.00339
24	252	7,914	0.00303	64	232	18,842	0.00340
25	212	8,126	0.00308	65	178	19,020	0.00342
26	533	8,659	0.00300	66	1,717	20,737	0.00318
27	824	9,483	0.00285	67	406	21,143	0.00317
28	102	9,585	0.00292	68	406	21,549	0.00316
29	73	9,658	0.00300	69	406	21,955	0.00314
30	422	10,080	0.00298	70	406	22,361	0.00313
31	74	10,154	0.00305	71	406	22,767	0.00312
32	113	10,267	0.00312	72	2	22,769	0.00316
33	263	10,530	0.00313	73	2	22,771	0.00321
34	184	10,714	0.00317	74	204	22,975	0.00322
35	4	10,718	0.00327	75	17	22,992	0.00326
36	68	10,786	0.00334	76	86	23,078	0.00329
37	61	10,847	0.00341	77	8	23,086	0.00334
38	69	10,916	0.00348	78	154	23,240	0.00336
39	458	11,374	0.00343	79	4	23,244	0.00340
40	3	11,377	0.00352	80	327	23,571	0.00339

(continued on next page)

Table 32 (continued)

Stoppage Number	Rounds Since Last Stoppage	Cumulative		Stoppage Number	Rounds Since Last Stoppage	Cumulative	
		Rounds Fired	Stoppage Rate			Rounds Fired	Stoppage Rate
81	196	23,767	0.00341	98	444	31,893	0.00307
82	50	23,817	0.00344	99	444	32,337	0.00306
83	24	23,841	0.00348	100	910	33,247	0.00301
84	349	24,190	0.00347	101	158	33,405	0.00302
85	831	25,021	0.00340	102	362	33,767	0.00302
86	6	25,027	0.00344	103	18	33,785	0.00305
87	321	25,348	0.00343	104	1,513	35,298	0.00295
88	583	25,931	0.00339	105	207	35,505	0.00296
89	51	25,982	0.00343	106	185	35,690	0.00297
90	21	26,003	0.00346	107	341	36,031	0.00297
91	278	26,281	0.00346	108	122	36,153	0.00299
92	1,154	27,435	0.00335	109	211	36,364	0.00300
93	2,238	29,673	0.00313	110	462	36,826	0.00299
94	444	30,117	0.00312	111	98	36,924	0.00301
95	444	30,561	0.00311	112	935	37,859	0.00296
96	444	31,005	0.00310	113	667	38,526	0.00293
97	444	31,449	0.00308	114	124	38,650	0.00295

Therefore, we excluded them from the data in Table 32 and counted only those stoppages for which rounds since last stoppage and cumulative rounds fired were reported. Accordingly, Table 32 shows only 114 stoppages out of the total of 166 reported by Lockheed. (Our estimate of MRTS is therefore probably optimistic!)

Figure 59 shows the graph in full-logarithmic coordinates of the cumulative stoppage rate versus cumulative rounds fired from Table 32. The straight line on this graph represents the maximum-likelihood estimate of the expected cumulative failure rate under the hypothesis that the expected cumulative failure rate has the parametric form $c(t) = \lambda t^{\beta-1}$ for $t > 0$. λ and β[1] are positive constants estimated from the data by using the

[1] $1-\beta$ corresponds to the α used in Duane's and General Electric's RPM reliability-growth models.

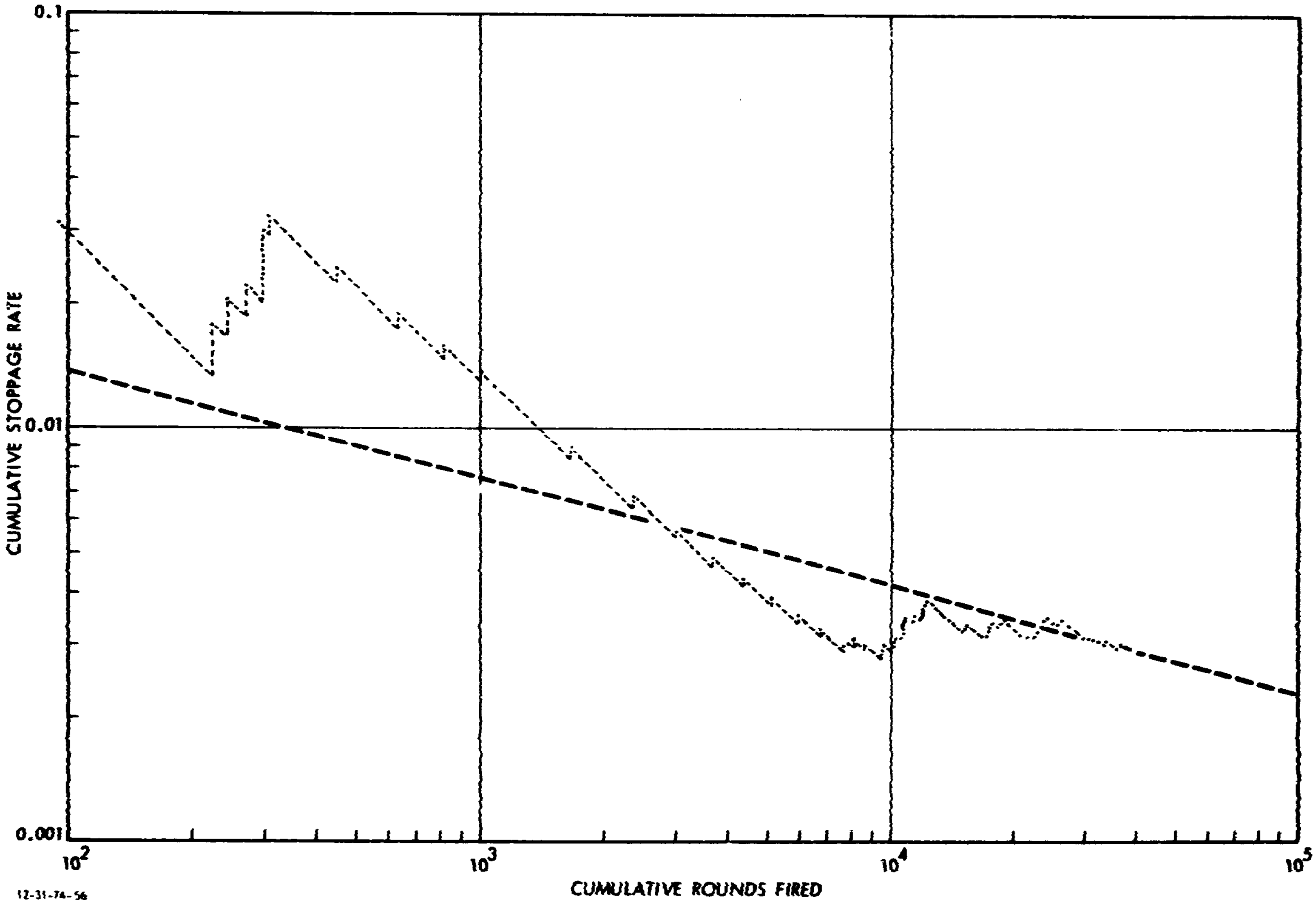

Figure 59. AH-56A CUMULATIVE STOPPAGE RATE VERSUS ROUNDS FIRED FOR THE XM-51 40-mm GRENADE-LAUNCHER SYSTEM

method of maximum likelihood. A full discussion of the statistical methods that we have used in our analysis may be found in Donelson [15]. For the data in Table 32, the maximum-likelihood estimates are $\hat{\lambda} = 0.046$ and $\hat{\beta} = 0.74$. A 95-percent confidence interval for β (and therefore for the slope of the straight line in Figure 59) is given by [0,598,0.869]. The maximum-likelihood estimate of MRTS after 38,650 rounds is 458 MRTS.

b. XM-52 30-mm Gun System

Testing on this weapon system began in January 1969 and continued until 21 December 1971. The data for our analysis come from Reference [14, Vol. I, pp. 109-27]. Lockheed reported firing a total of 33,432 rounds (or 26 percent of the programmed 128,000 rounds) during this testing period. Lockheed also reported a total of 107 stoppages, of which 50 were due to CFM. The deduction of nonchargeable failures and failures for which fixes had been developed reduced the count of net chargeable failures due to CFM to 12. Thus, Lockheed reported the reliability of the XM-52 Gun System as 2,786 MRTS--i.e., 33,432/12 = 2,786.

Again, we performed our reliability analysis for the entire weapon system including the gun and ammunition. Thus, we have counted stoppages due to both CFM and GFM. Table 33 contains the stoppage history for the XM-52 Gun System. Our data again differ from the data reported by Lockheed [14, Vol. I, pp. 109-27]. The reasons for these discrepancies are the same as explained earlier for the XM-51 Grenade-Launcher System.

Figure 60 contains the graph in full-logarithmic coordinates of the cumulative-stoppage-rate data from Table 33. The straight line in Figure 60 represents the maximum-likelihood estimate of the expected cumulative failure rate under the hypothesis that the expected cumulative failure rate has the parametric form $c(t) = \lambda t^{\beta-1}$ for $t > 0$. The maximum-likelihood estimates of λ and β for the data from Table 33 are $\hat{\lambda} = 0.044$ and $\hat{\beta} = 0.73$.

Table 33. STOPPAGE HISTORY AND CUMULATIVE STOPPAGE RATE FOR THE XM-52 30-mm GUN SYSTEM

Stoppage Number	Rounds Since Last Stoppage	Cumulative		Stoppage Number	Rounds Since Last Stoppage	Cumulative	
		Rounds Fired	Stoppage Rate			Rounds Fired	Stoppage Rate
1	76	76	0.01316	48	458	11,762	0.00408
2	0	76	0.02632	49	705	12,467	0.00393
3	70	146	0.02055	50	2,983	15,450	0.00324
4	80	226	0.01770	51	136	15,586	0.00327
5	56	282	0.01773	52	446	16,032	0.00324
6	364	646	0.00929	53	186	16,218	0.00327
7	728	1,374	0.00509	54	125	16,343	0.00330
8	663	2,037	0.00393	55	633	16,976	0.00324
9	663	2,700	0.00333	56	27	17,003	0.00329
10	664	3,364	0.00297	57	24	17,027	0.00335
11	150	3,514	0.00313	58	25	17,052	0.00340
12	381	3,895	0.00308	59	24	17,076	0.00346
13	19	3,914	0.00332	60	149	17,225	0.00348
14	244	4,158	0.00337	61	51	17,276	0.00353
15	26	4,184	0.00359	62	950	18,226	0.00340
16	27	4,211	0.00380	63	255	18,481	0.00341
17	27	4,238	0.00401	64	712	19,193	0.00333
18	87	4,325	0.00416	65	26	19,219	0.00338
19	31	4,356	0.00436	66	51	19,270	0.00343
20	0	4,356	0.00459	67	181	19,451	0.00344
21	22	4,378	0.00480	68	25	19,476	0.00349
22	0	4,378	0.00503	69	155	19,631	0.00351
23	24	4,402	0.00522	70	659	20,290	0.00345
24	1	4,403	0.00545	71	3,268	23,558	0.00301
25	28	4,431	0.00564	72	497	24,055	0.00299
26	40	4,471	0.00582	73	302	24,357	0.00300
27	17	4,488	0.00602	74	302	24,659	0.00300
28	302	4,790	0.00585	75	464	25,123	0.00299
29	160	4,950	0.00586	76	687	25,810	0.00294
30	57	5,007	0.00599	77	424	26,234	0.00294
31	430	5,437	0.00570	78	885	27,119	0.00288
32	54	5,491	0.00583	79	450	27,569	0.00287
33	360	5,851	0.00564	80	215	27,784	0.00288
34	52	5,903	0.00576	81	142	27,926	0.00290
35	1	5,904	0.00593	82	71	27,997	0.00293
36	751	6,655	0.00541	83	416	28,413	0.00292
37	53	6,708	0.00552	84	455	28,868	0.00291
38	1,023	7,731	0.00492	85	455	29,323	0.00290
39	42	7,773	0.00502	86	455	29,778	0.00289
40	179	7,952	0.00503	87	455	30,233	0.00288
41	0	7,952	0.00516	88	92	30,325	0.00290
42	1,649	9,601	0.00437	89	750	31,075	0.00286
43	42	9,643	0.00446	90	235	31,310	0.00287
44	609	10,252	0.00429	91	127	31,437	0.00289
45	7	10,259	0.00439	92	1,016	32,453	0.00283
46	44	10,303	0.00446	93	679	33,132	0.00281
47	1,001	11,304	0.00416				

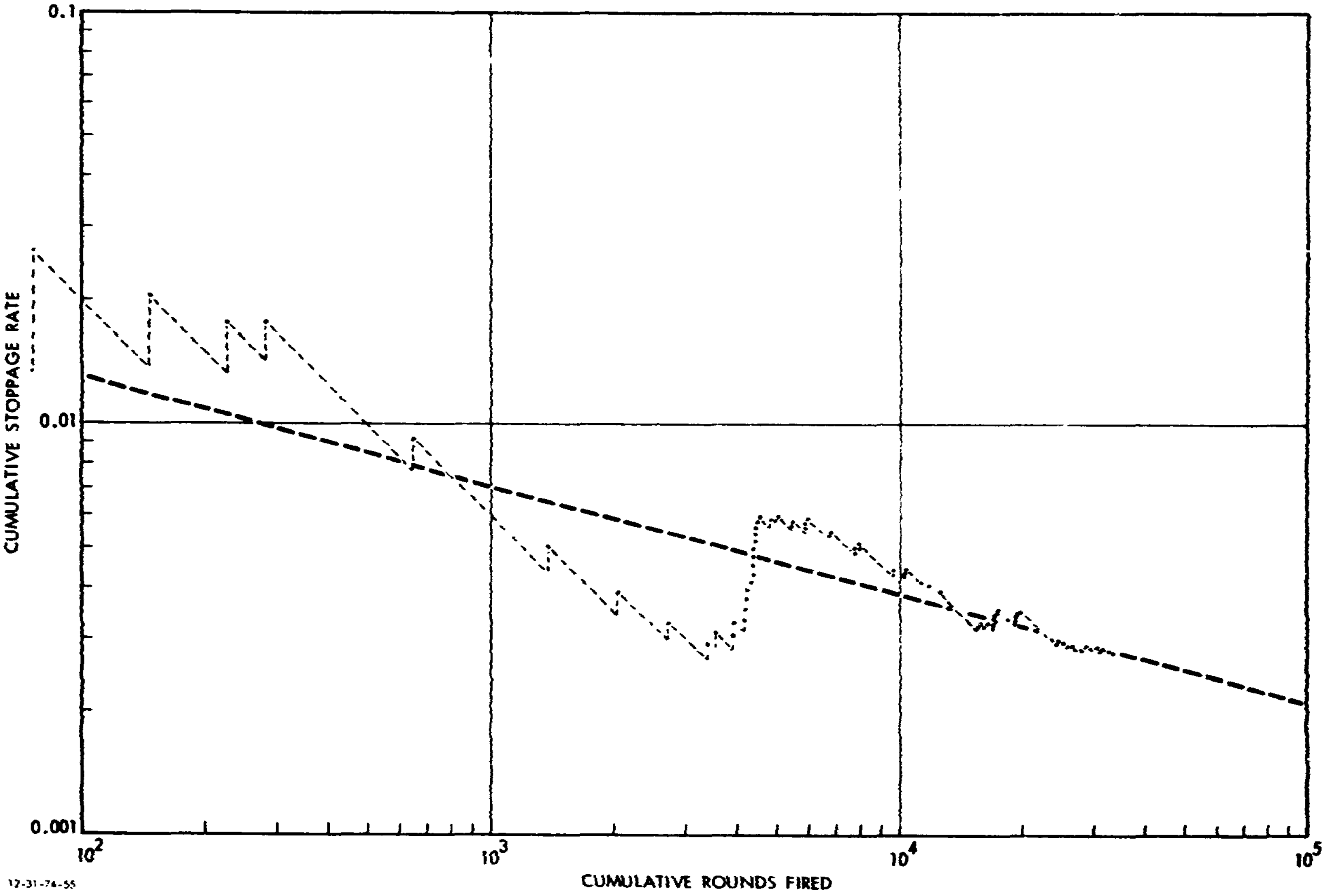

Figure 60. AH-56A CUMULATIVE STOPPAGE RATE VERSUS ROUNDS FIRED FOR THE XM-52 30-mm GUN SYSTEM

A 95-percent confidence interval for β is given by [0.578, 0.875]. The maximum-likelihood estimate of MRTS for the XM-52 after 33,132 rounds fired is 484 MRTS.

c. <u>XM-53 7.62-mm Machine-Gun System</u>

Testing on this weapon system began in April 1968 and continued until 29 August 1969, at which time the XM-53 was deleted from the AH-56A program and replaced with the XM-51 Grenade-Launcher System [14, Vol. I, p. 129]. However, we have included the XM-53 in our study because it exhibited the most rapid reliability growth of any of the three gun systems on the AH-56A.

The data used in our analysis come from the XM-53 Armament Stoppage History [14, Vol. I, pp. 132-39]. Lockheed reported firing a total of 161,003 rounds (or 15 percent of the programmed 1,056,000 rounds) and a total of 72 stoppages, of which 43 were due to CFM. There were a total of 16 net chargeable failures after deducting nonchargeable failures and failures for which fixes had been developed. Thus, Lockheed reported the reliability of the XM-53 Machine-Gun System as 10,063 MRTS--i.e., 161,003/16 = 10,063.

The reliability-growth analysis we have performed here is for the entire XM-53 Gun System and includes both the gun and ammunition. Therefore, we have included stoppages due to both CFM and GFM in the XM-53 stoppage history in Table 34. Our data again differ somewhat from the data reported by Lockheed [14, Vol. I, pp. 132-39]. Again, this difference is due to arithmetic and typographical errors and to lost data.

Figure 61 contains the graph of the cumulative-stoppage-rate data for the XM-53 from Table 34. The dashed line in Figure 61 represents the maximum-likelihood estimate of the expected cumulative failure rate under the hypothesis that the expected cumulative failure rate has the parametric form

Table 34. STOPPAGE HISTORY AND CUMULATIVE STOPPAGE RATE FOR THE XM-53 7.62-mm MACHINE-GUN SYSTEM

Stoppage Number	Rounds Since Last Stoppage	Cumulative		Stoppage Number	Rounds Since Last Stoppage	Cumulative	
		Rounds Fired	Stoppage Rate			Rounds Fired	Stoppage Rate
1	69	69	0.01449	33	315	18,609	0.001770
2	18	87	0.02299	34	238	18,847	0.001800
3	27	114	0.02632	35	4,628	23,475	0.001490
4	35	149	0.02685	36	24,973	48,448	0.000743
5	4	153	0.03268	37	3,775	52,223	0.000709
6	153	306	0.01961	38	617	52,840	0.000719
7	351	657	0.01065	39	2,058	54,898	0.000710
8	120	777	0.01030	40	13,406	68,304	0.000586
9	110	887	0.01015	41	4,114	72,418	0.000566
10	64	951	0.01052	42	9,904	82,322	0.000510
11	1,087	2,038	0.00540	43	5,733	88,055	0.000488
12	163	2,201	0.00545	44	7,168	95,223	0.000462
13	241	2,442	0.00532	45	9,664	104,887	0.000429
14	94	2,536	0.00552	46	3,690	108,577	0.000424
15	29	2,565	0.00585	47	2,913	111,490	0.000422
16	106	2,671	0.00599	48	10,846	122,336	0.000392
17	143	2,814	0.00604	49	324	122,660	0.000399
18	5,688	8,502	0.00212	50	10,101	132,761	0.000377
19	148	8,650	0.00220	51	4,057	136,818	0.000373
20	108	8,758	0.00228	52	647	137,465	0.000378
21	570	9,328	0.00225	53	184	137,649	0.000385
22	1,358	10,686	0.00206	54	1,471	139,120	0.000388
23	1,712	12,398	0.00186	55	135	139,255	0.000395
24	50	12,448	0.00193	56	30	139,285	0.000402
25	0	12,448	0.00201	57	248	139,533	0.000409
26	177	12,625	0.00206	58	115	139,648	0.000415
27	99	12,724	0.00212	59	10,573	150,221	0.000393
28	1,548	14,272	0.00196	60	1,138	151,359	0.000396
29	848	15,120	0.00192	61	24	151,383	0.000403
30	140	15,260	0.00197	62	24	151,407	0.000409
31	416	15,676	0.00198	63	2,990	154,397	0.000408
32	2,618	18,294	0.00175	64	4,174	158,571	0.000404

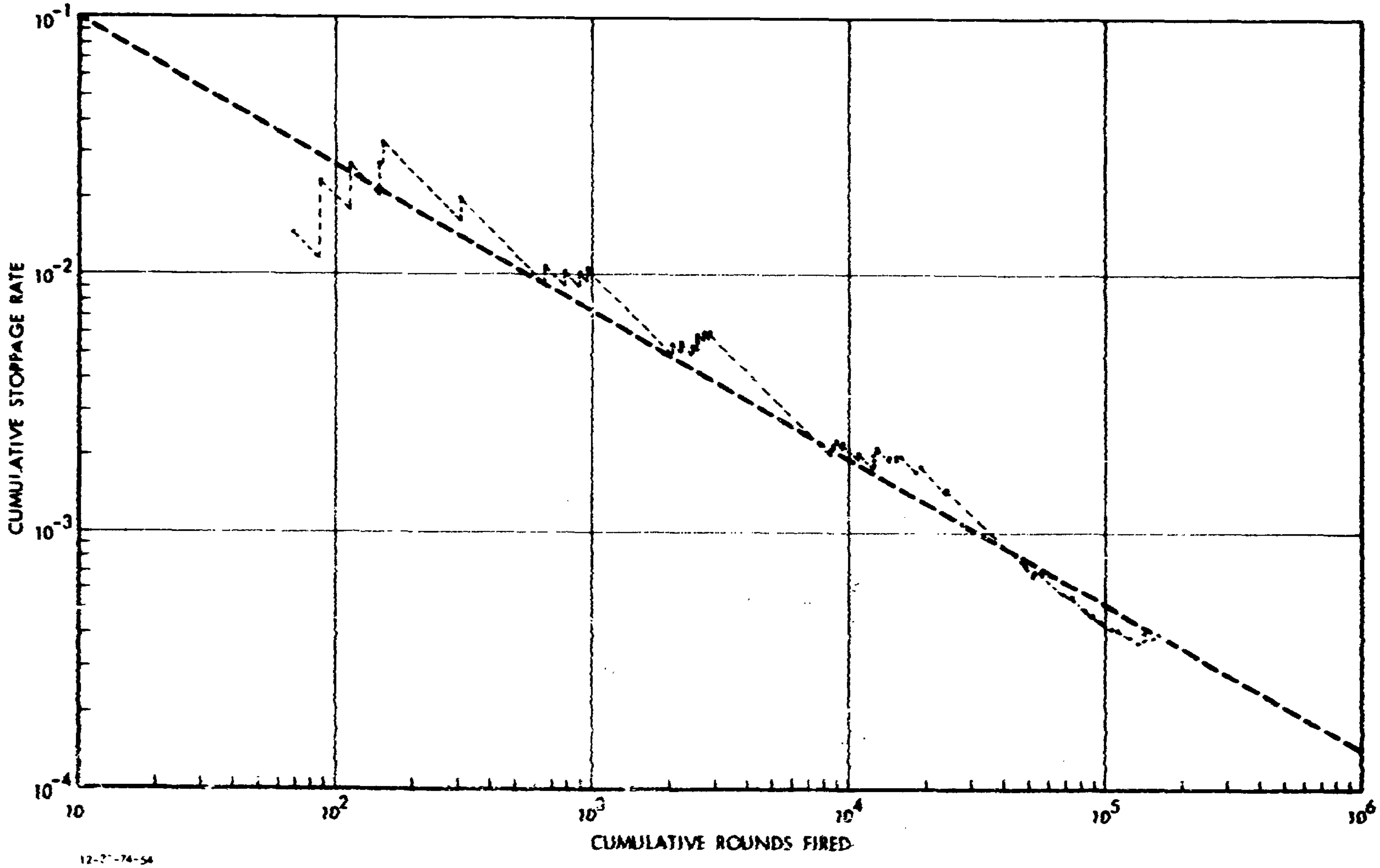

Figure 61. AH-56A CUMULATIVE STOPPAGE RATE VERSUS ROUNDS FIRED FOR THE XM-53 7.62-mm MACHINE-GUN SYSTEM

$c(t) = \lambda t^{\beta-1}$ for $t > 0$. The maximum-likelihood estimates of λ and β for the data from Table 34 are $\hat{\lambda} = 0.369$ and $\hat{\beta} = 0.431$. A 95-percent confidence interval for β is given by [0.319, 0.529]. Under the hypothesis that the instantaneous stoppage rate has the form $\lambda(t) = \lambda\beta t^{\beta-1}$ for $t > 0$, the maximum-likelihood estimate of MRTS for the XM-53 after 158,571 rounds fired is 5,773 MRTS.

Our calculations clearly indicate that the XM-53 Gun System experienced a very rapid improvement in reliability during the period of time it was being tested.

3. Conclusions

Table 35 compares Lockheed's and IDA's estimates of MRTS for the XM-51, XM-52, and XM-53 weapon systems. The estimates in Table 35 apply to the weapon systems at the end of the testing program.

Table 35. COMPARISON OF LOCKHEED'S AND IDA'S ESTIMATES OF MRTS FOR THE XM-51, XM-52, AND XM-53 WEAPON SYSTEMS

Weapon System	Estimate of MRTS	
	By Lockheed	By IDA
XM-51	2,895	458
XM-52	2,785	484
XM-53	10,063	5,773

For the XM-51 and XM-52, Lockheed's estimates of MRTS are approximately six times IDA's; for the XM-53, their estimate is almost double [illegible]'s. Since the test period on the XM-53 lasted only 17 month[illegible] before its discontinuance, it appears that Lockheed personnel were unable to apply the "Deduction of Failures" provisions of Paragraph 7.4.6.5 (see Appendix A, below) to the

same extent as was done for the XM-51 and XM-52. Thus, Lockheed personnel deducted fewer chargeable failures in making their estimate of MRTS for the XM-53. Hence, Lockheed's estimate of MRTS for the XM-53 is closer to our estimate than it is for the other weapon systems. However, in every case, Lockheed's estimates of MRTS are more optimistic than ours, because they counted fewer failures than we did.

We believe that reliability estimates based on the deduction of failures tend to be overly optimistic. We recommend that, in future contracts, reliability estimates based on all failures should be required--in addition to the more optimistic estimates based on deducted failures.

Chapter IV

HELICOPTER ENGINE DATA

A. ANALYSIS OF T700-ENGINE RELIABILITY IMPROVEMENT*

The data used in this analysis were obtained by IDA from the Project Manager's Office (PMO), Utility Tactical Transport Aircraft System (UTTAS). In fulfillment of contractual obligations, these data are supplied to the UTTAS PMO by General Electric Company, the prime contractor for the T700 engine.

Appendix B (below) contains paragraphs (which specify the reliability goals, failure definitions, excluded failures, and measurement procedures) that are quoted directly from Reference [23].

The development and testing program has been apportioned 7,200 hours of test time in which to achieve the goal of 1,200 hours MTBF. A total of 2,268 hours of testing had been completed as of 1 August 1974.

1. Data Analysis by IDA

The statistical analysis we have performed using T700 engine-test data has three objectives:

(1) To determine the rate of reliability improvement.
(2) To evaluate T700 reliability as of 10 June 1974.
(3) To forecast T700 engine reliability at future points in the test program.

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a. **Test Data**

Table 36 contains a list of all T700 engine failures that were validated in the T700 testing program as of 1 August 1974. All these failures are chargeable under the definitions of Paragraph 3.40.3 (see Appendix B, below).

A total of 36 failures had been validated on the T700 engine as of 10 June 1974, at which time 2,071 hours of testing had been completed. As of 1 August 1974, 2,268 hours of testing had been completed. However, our analysis uses only the data through 10 June 1974 (i.e., 2,071 test hours), because additional failures that may have occurred between 10 June and 1 August 1974 may not have been completely analyzed and reported as of the assessment cut-off date (1 August 1974).

Table 36 shows for each failure the component that failed, the date the failure occurred, the engine serial-build on which the failure was detected, the cumulative test hours on each T700 prototype engine, and the cumulative test time on all T700 prototypes as of the date on which the failure occurred. An asterisk (*) indicates an engine that failed. It is to be noted that data for engine #002 has not been included in Table 36, since engine #002 (a gas generator) is not intended to perform as a T700 engine. The parallel failures are indicated by a "P" on the left side of Table 36. These are failures where the same component has failed more than once, either on the same engine or on separate engines.

"ATE" on the left side of Table 36 indicates chargeable failures that have been eliminated because the components involved have passed acceptance tests. These failures occurred when defective components were left on engines so that testing could continue. We have performed two identical statistical analyses--one using the data on all failures in Table 36, the other using the data from Table 36 with the ATE failures eliminated.

Table 36. T700-ENGINE COMPONENT FAILURES OCCURRING IN DEVELOPMENT TESTS

[Includes parallel failures]

Failure Number	Notes[1]	Component	Event Date	Engine Serial-Build	Serial-Hours Engine Number 1	3	4	5	6	Cumulative Time - All Engines
1		Anti-Ice and Bleed Valve	4/6/73	001-1B	*89	--	--	--	--	89
2		Primer Nozzle	4/27/73	001-1D	*127	--	--	--	--	127
3		Ignition Circuitry-Igniter	5/1/73	001-1D	*127	0	--	--	--	127
4		Hydrochemical Control Unit--Pressure-Regulating Valve (PRV)	5/22/73	001-1E	*178	34	--	--	--	212
5		Oil Filter Bypass Sensor	5/24/73	001-1E	*184	34	--	--	--	218
6		P_3 Sensing Hose - Air Lines	6/1/73	001-1E	*234	34	--	--	--	268
7		Axis G Bearing Anti-Rotation Pin, Inlet Particle Separator (IPS) Blower	6/19/73	003-1C	259	*65	0	--	--	324
8	(P)	#4 Bearing - (Skidding)	7/6/73	004-1D	271	128	*16	--	--	415
9		IPS Blower - (Bonding failed) (Component failed at 25 hours)	7/10/73	003-1G	271	*141	16	--	--	428
10	(P)	#4 Bearing - (Skidding)	7/12/73	004-xx[2]	271	141	*20	--	--	432
*11	(ATE)	Electronic Control Unit (ECU) - ($T_{4.5}$ Fluctuation)	8/24/73	003-1P	271	*196	81	--	--	548
12	(ATE)	Engine Lube System (A Sump-High discharge pressure)	9/10/73	004-1H	271	214	*93	--	--	578
13	(ATE)	Combustion Liner (Lean blowout)	9/10/73	004-1H	271	214	*93	--	--	578
14	(ATE)	ECU ($T_{4.5}$ and Torque Oscillation)	9/12/73	004-1H	271	214	*103	--	--	588
15	(ATE)	#4 Bearing-Trilobe (Component failed at 16.5 hours)	10/2/73	003-2A	271	*225	121	--	--	617
16	(P)	Turbine Rotor Assembly (Stage-1 Cooling Plate)	10/30/73	003-2D	271	*316	160	--	--	747
17		P_3 Hose - Air Lines (Broken)	11/14/73	003-2E	271	*323	232	--	--	826
18		Wiring Harness, PT Speed and Overspeed	11/16/73	003-2E	271	*348	253	--	--	872
19	(ATE)	Sequence Valve (Hung Start)	11/27/73	005-1A	272	350	277	*0	--	899
20		InterBalance Piston (IBP) Seal (Rotor seizure)	11/29/73	005-1B	279	350	335	*10	--	974
21		Turbine Rotor Assembly (Stage-1 Cooling Plate)	12/6/73	005-xx[2]	279	350	365	*56	--	1,050
22	(P)	Turbine Rotor Assembly (Stage-1 Cooling Plate)	12/7/73	004-xx[2]	279	350	*365	56	--	1,050
23		Hydromechanical Unit (HMU) PRV #2	1/10/74	005-1H	367	350	431	*192	--	1,340
24		HMU PRV #3 (Component failed at 123 hours)	1/16/74	005-1H	367	350	431	*235	--	1,383
25	(P)	HMU PRV #4 (Hot Start)	1/16/74	005-1H	367	350	431	*235	0	1,383

b. Statistical Model of Reliability Growth

In modeling reliability growth on the T700 engine, we assume that failures measured versus cumulative test time t occur according to a Non-Homogeneous Poisson Process (NHPP) $\{N(t), t \geq 0\}$, where N(t) denotes the number of failures in the interval [0,t]. The time variable t measures cumulative test time on all prototype engines. Let m(t), which is called the mean-value function of the NHPP N(t), denote the expected number of failures in the interval [0,t]--i.e., m(t) = E(N(t)). Specifically, we assume that our NHPP has a mean-value function of the form

$$m(t) = \lambda t^{\beta}$$

for $t \geq 0$, where λ and β[1] are positive constants.

Let $S_0 \equiv 0$; and for n = 1, 2, ..., let S_n denote the random time of occurrence of the n^{th} failure. Again, time is to be understood here as cumulative test time. For n = 1, 2, ..., let $T_n = S_n - S_{n-1}$ be the elapsed (random) time between the occurrence of the $(n-1)^{st}$ and n^{th} failures. Let τ_n denote the expected value of T_n--i.e., $\tau_n = E(T_n)$. Then τ_n is the expected elapsed time between the $(n-1)^{st}$ and n^{th} failures (i.e., MTBF). τ_n is given in terms of β, λ; and n, by the equation

$$\tau_n = \frac{1}{\beta}\left(\frac{1}{\lambda}\right)^{\frac{1}{\beta}} \frac{\Gamma\left(\frac{1}{\beta} + n - 1\right)}{\Gamma(n)} \qquad (7)$$

for n = 1, 2, ..., where $\Gamma(\cdot)$ is the Euler gamma (factorial) function and $\Gamma(n) = (n - 1)!$. Since λ and β are not known in advance, we use the method of maximum-likelihood estimation to obtain strongly consistent estimators for λ and β in terms of

[1] $1-\beta$ corresponds to the α used in Duane's and General Electric's RPM reliability-growth models.

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observed-failure time data. (See Donelson [15] for a thorough discussion of these statistical techniques.) We denote these estimates by $\hat{\lambda}$ and $\hat{\beta}$.

Once we have obtained estimates of λ and β, we may substitute them into Equation (7) to obtain estimates of τ_n for various values of n. Thus, if we have observed m failures (the m^{th} failure occurring at time s_m), we can estimate that the achieved or current MTBF of the system at time $t = s_m$ is τ_m. If we let σ_n denote the expected time of occurrence of the n^{th} failure (i.e., $\sigma_n = E(S_n)$), we can also estimate that at time $t = \sigma_n$ the MTBF of the system is τ_n. For the purpose of this computation, σ_n is given in terms of λ, β; and n, by the formula

$$\sigma_n = \left(\frac{1}{\lambda}\right)^{\frac{1}{\beta}} \frac{\Gamma\left(\frac{1}{\beta} + n\right)}{\Gamma(n)} \tag{8}$$

for n = 1, 2, ...

c. Results of Statistical Analysis

Table 37 contains the cumulative failure rate for the test data from Table 36, including the ATE failures. The cumulative failure rate is obtained by dividing cumulative failures by cumulative test-hours. The maximum-likelihood estimates of λ and β for the data in Table 37 are

$$\hat{\lambda} = 0.022 \quad \text{and} \quad \hat{\beta} = 0.968 \ .$$

A 95-percent confidence interval for β (using the data in Table 37) is given by the interval [0.655,1.277]. In Figure 62 we have plotted the cumulative failure rate from Table 37 versus cumulative test-hours on full logarithmic scale. The dashed line in Figure 62 represents the maximum-likelihood estimate of the expected cumulative-failure-rate function under the hypothesis that the mean-value function has the form $m(t) = \lambda t^{\beta}$. In this case the expected cumulative failure rate is

Table 37. CUMULATIVE FAILURES, TEST-HOURS, AND RATE FOR THE T700 ENGINE-TEST DATA FROM TABLE 36 (INCLUDING ATE FAILURES)

Failure Number	Cumulative Test-Hours	Cumulative Failure Rate	Failure Number	Cumulative Test-Hours	Cumulative Failure Rate
1	89	0.0112	19	899	0.0211
2	127	0.0157	20	974	0.0205
3	127	0.0236	21	1,050	0.0200
4	212	0.0189	22	1,050	0.0210
5	218	0.0229	23	1,340	0.0172
6	268	0.0224	24	1,383	0.0174
7	324	0.0216	25	1,383	0.0181
8	415	0.0193	26	1,416	0.0184
9	428	0.0210	27	1,450	0.0186
10	432	0.0231	28	1,465	0.0191
11	548	0.0201	29	1,645	0.0176
12	578	0.0208	30	1,683	0.0178
13	578	0.0225	31	1,687	0.0184
14	588	0.0238	32	1,928	0.0166
15	617	0.0243	33	1,930	0.0171
16	747	0.0214	34	1,974	0.0172
17	826	0.0206	35	2,012	0.0174
18	872	0.0206	36	2,071	0.0174

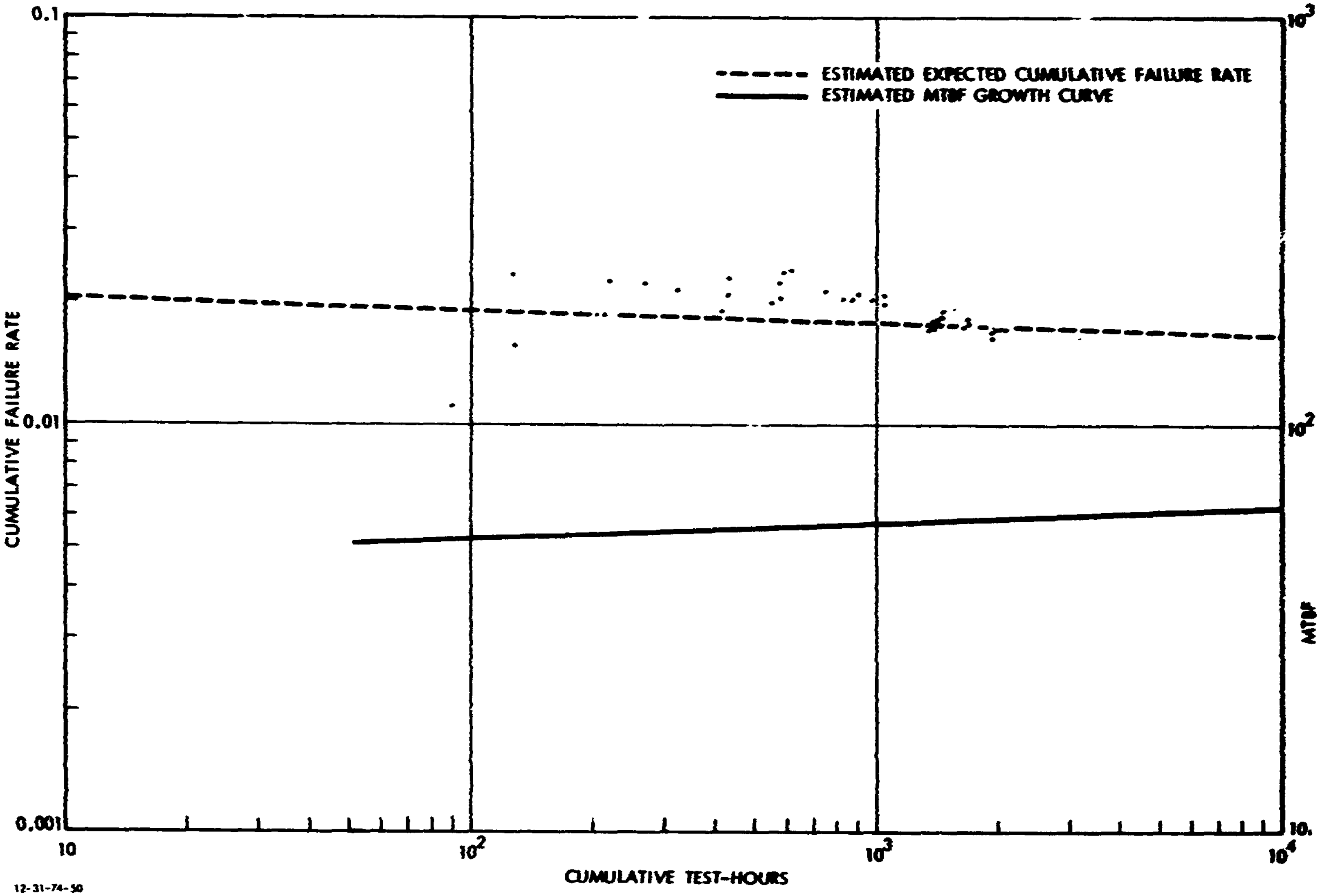


Figure 62. CUMULATIVE FAILURE RATE FOR FIVE T700 ENGINE PROTOTYPES (ATE FAILURES INCLUDED)

$\rho(t) = m(t)/t = \lambda t^{\beta-1}$. It is to be noted that this function is just a straight line with slope $\beta-1$ when it is plotted on full logarithmic scale.

The solid line in Figure 62 gives the estimated MTBF for the T700 engine at various times in the test program. This estimate is obtained by plotting τ_n given by Equation (7) versus σ_n given by Equation (8) for $n = 1, 2, \ldots$ (using the maximum-likelihood values of λ and β given in the preceding paragraph).

The estimate $\hat{\tau}$ of current MTBF after 36 failures (ATE failures included) and 2,071 cumulative test-hours (as of 10 June 1974) is

$$\hat{\tau} = 59.4 \text{ hours} .$$

The estimated standard deviation of the time to failure (as of 10 June 1974) is

$$\sigma_T = 59.5 \text{ hours} .$$

This compares with a current estimate (given to us by the UTTAS PMO) of 753 hours MTBF, made by General Electric.

Projecting the trend (i.e., using the above estimated values of λ and β) that has been established using the data in Table 40, we estimate from Equation (8) that the expected time for failure #121 is 7,250 hours. At this point the estimated expected value (MTBF) of the 121st failure time-interval is only 61.9 hours. Thus, the present trend when projected into the future indicates virtually no reliability improvement for the T700 engine. Unless there are dramatic improvements in the near future (which are unlikely, given the lead time required to change the makeup of such a development program), we believe that it is highly improbable that the T700 engine-development program will achieve the 1,200-hour MTBF goal.

Table 38 contains the cumulative failure-rate for the test data from Table 36 after the ATE failures have been eliminated. The maximum-likelihood estimates of λ and β for the data in Table 38 are

$$\hat{\lambda} = 0.027 \quad \text{and} \quad \hat{\beta} = 0.905 \ .$$

A 95-percent confidence interval for β (using the data in Table 38) is given by the interval [0.569,1.237].

Figure 63 contains a plot of the cumulative failure-rate from Table 38 versus cumulative test-hours. Again, the dashed line in Figure 63 represents the maximum-likelihood estimate of the expected cumulative failure-rate for the data from Table 38, and the solid line shows the estimated MTBF as a function of cumulative test-hours. We note that when the ATE failures are eliminated, the estimate of MTBF as of 10 June 1974 (i.e., after 2,071 test-hours) is

$$\hat{\tau} = 84.6 \text{ hours} \ .$$

Using the maximum-likelihood values of λ and β for the data in Table 38, the expected number of failures in 7,200 hours of testing is 84--the expected time of occurrence of the 84^{th} failure being 7,261 hours. The expected value (MTBF) of the 84^{th} failure time-interval in this case is 95.37 hours. Thus, even with the ATE failures eliminated, the predicted MTBF at the end of 7,200 hours of testing is only 10 hours above the current estimate--the predicted MTBF achievement being slightly less than eight percent of the 1,200-hour MTBF goal.

Table 38. CUMULATIVE FAILURES, TEST-HOURS, AND RATE FOR THE T700 ENGINE-TEST DATA FROM TABLE 36 (WITH ATE FAILURES ELIMINATED)

Failure Number	Cumulative Test-Hours	Cumulative Failure Rate	Failure Number	Cumulative Test-Hours	Cumulative Failure Rate
1	89	0.0112	15	1,050	0.0143
2	127	0.0157	16	1,050	0.0152
3	127	0.0236	17	1,340	0.0127
4	212	0.0189	18	1,383	0.0130
5	218	0.0229	19	1,383	0.0137
6	268	0.0224	20	1,416	0.0141
7	324	0.0216	21	1,450	0.0145
8	415	0.0193	22	1,465	0.0150
9	428	0.0210	23	1,645	0.0140
10	432	0.0231	24	1,683	0.0143
11	747	0.0147	25	1,687	0.0148
12	826	0.0145	26	2,012	0.0129
13	872	0.0149	27	2,071	0.0130
14	974	0.0144			

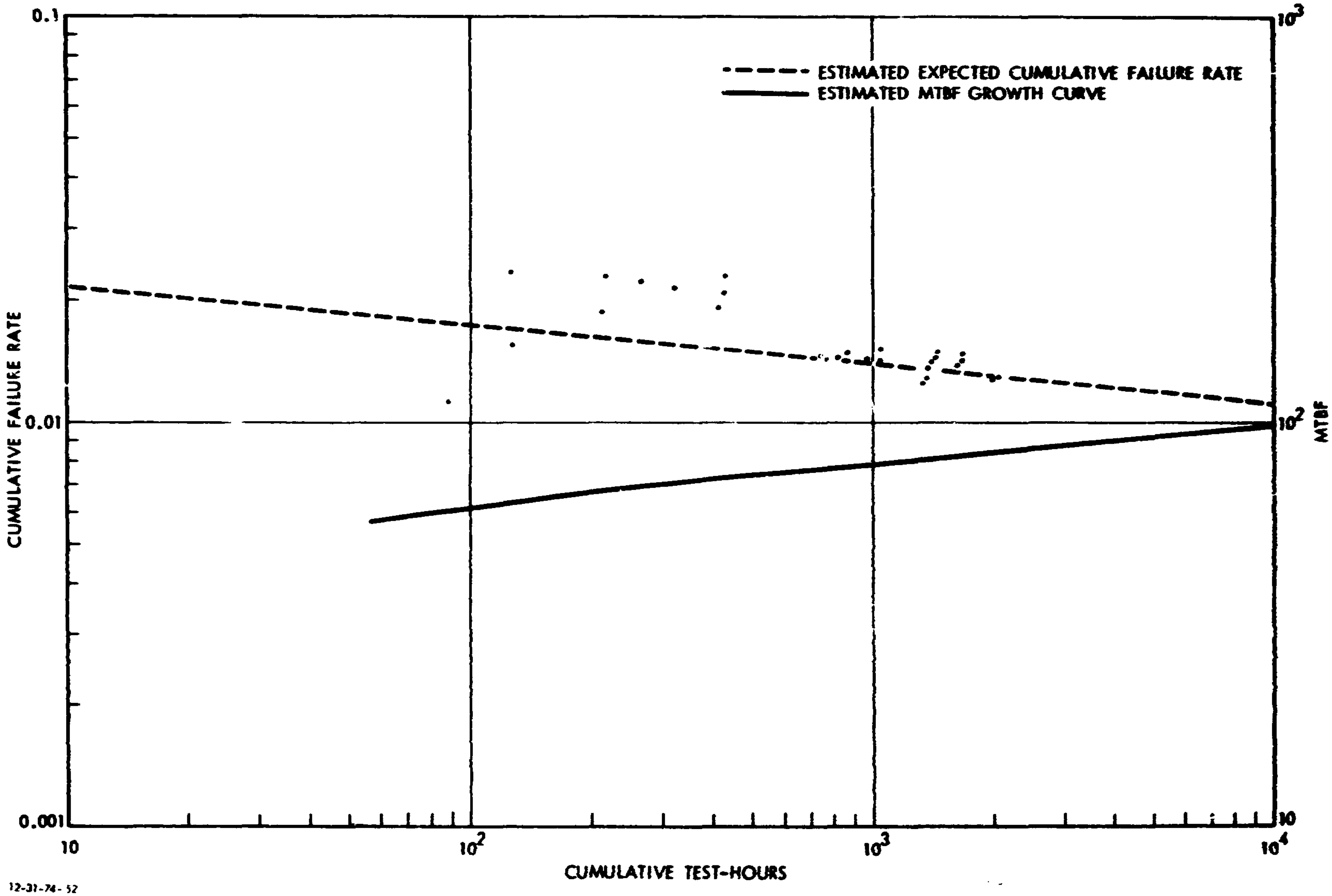


Figure 63. CUMULATIVE FAILURE RATE FOR FIVE T700 ENGINE PROTOTYPES (ATE FAILURES EXCLUDED)

2. Conclusions

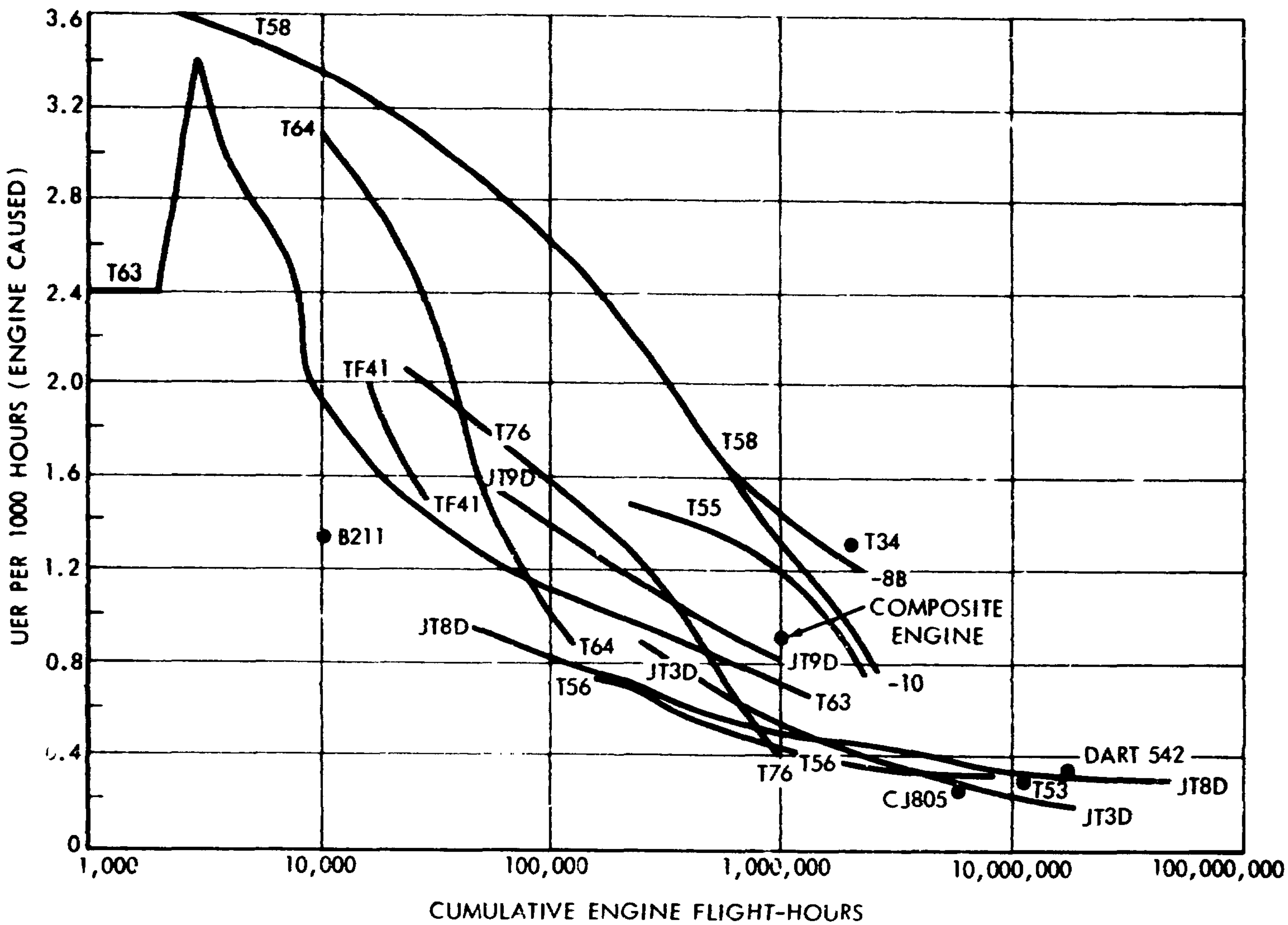
After 2,071 hours of testing (about 29 percent of the 7,200 hours allotted to testing), the T700 engine-development program has achieved only seven percent of the 1,200-hour MTBF goal. The rate (trend) of reliability improvement that has been established thus far is minimal and is not sufficient to achieve the 1,200 MTBF goal after 7,200 hours of testing. In fact, we estimate that less than 10 percent of the 1,200-hour goal will be achieved, even after ATE failures are excluded (Figure 63).

B. MISCELLANEOUS ENGINE DATA

Figure 64 is taken from a Boeing Vertol report prepared under contract to the U.S. Army Air Mobility Research and Development Laboratory. Data for a lower number of cumulative engine flight-hours were obtained directly from the manufacturers of the T58, T64, and T63 helicopter engines. Although there is a wide scatter in the lines for the various engines, the figure shows definite reliability growth in unscheduled engine-removal rates--from a rate of roughly 3.0 around 1,000 hours to a rate of about 0.3 at 10 million hours. In most cases, engine power ratings are increased over time; this growth in power tends to work against growth in engine reliability.

Note that Figure 64 depicts *unscheduled* engine removal (UER) rates. As hours are accumulated, the *scheduled* removal rates also tend to decrease (as TBOs are increased), so that the total removal rates (scheduled and unscheduled)--though greater than the UER rates shown in Figure 64--should also decrease roughly proportionally to the UER rates.

Table 39 and Figures 65-69 are from a Lycoming report on the T53 engine [18A]. Table 39 presents the production and status history for the various T53 engine models, and Figure 65



SOURCES: REFERENCES [16], [17], AND [18].

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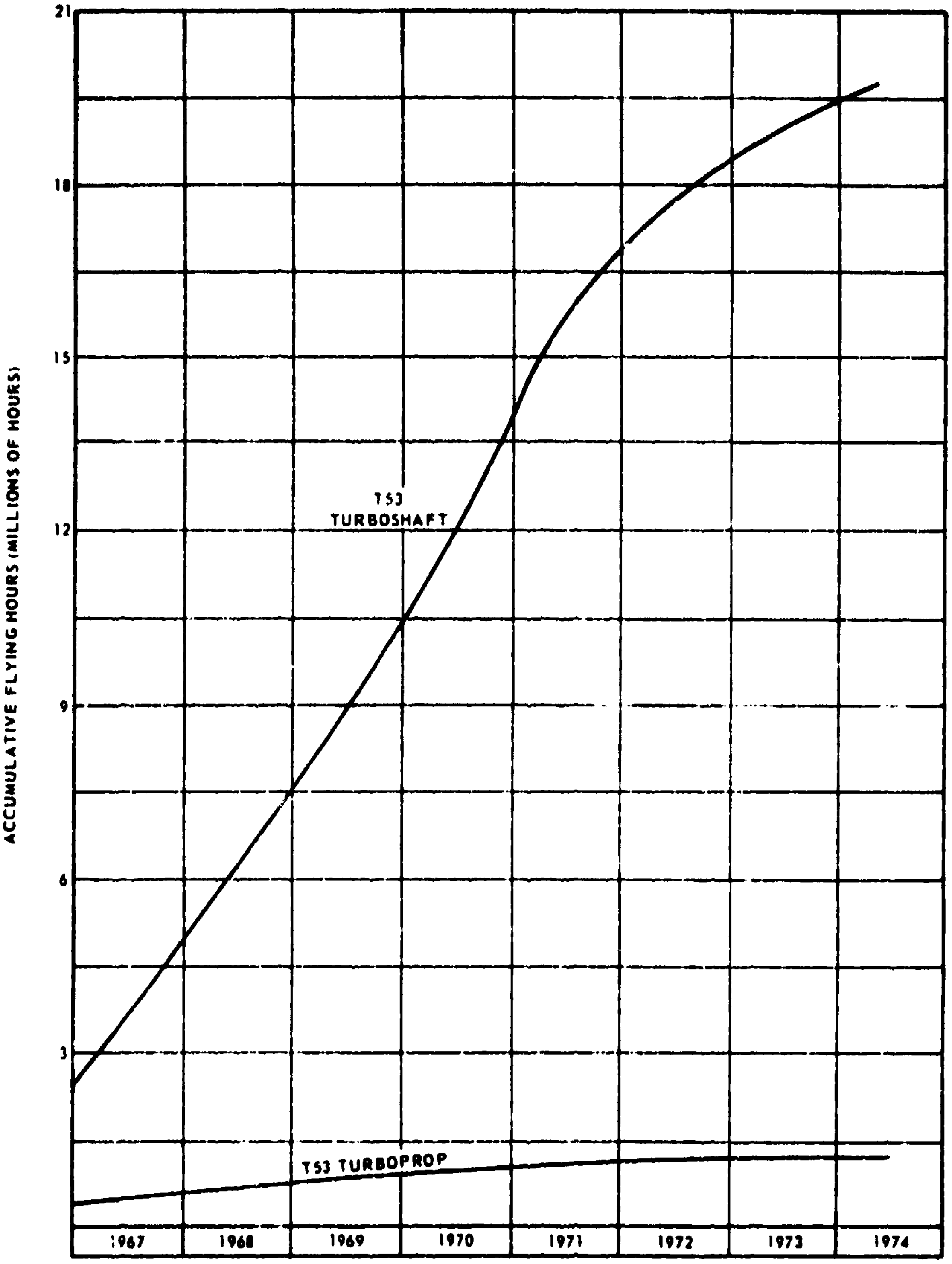
Figure 64. ENGINE RELIABILITY GROWTH

Table 39. T53 TURBOSHAFT PRODUCTION AND STATUS HISTORY (AS OF 30 JUNE 1974)

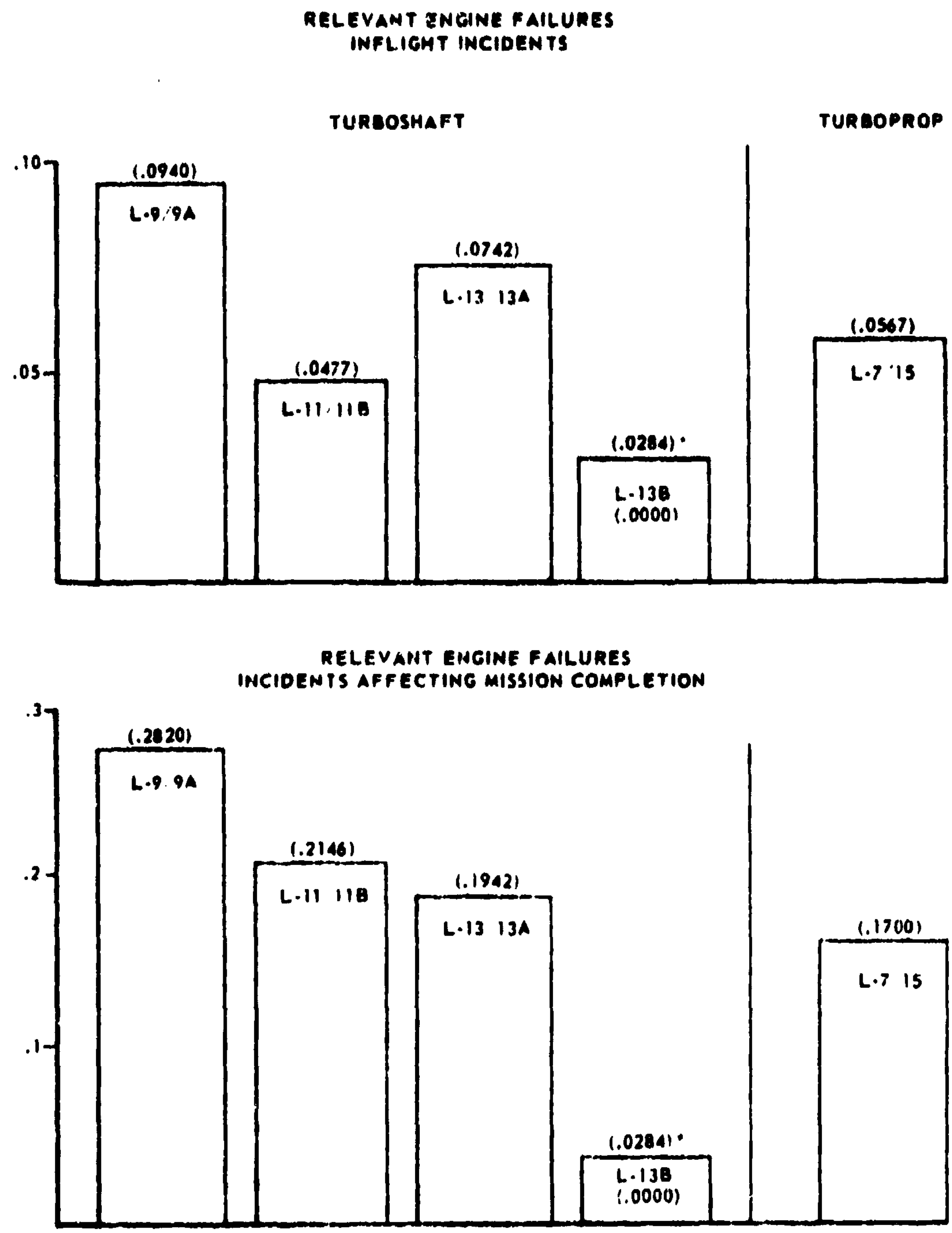
	L-1/1A	L-5	L-9/9A	L-11/11B	L-11C/11D	L-13/13A	L-13B
a. Engines Produced New	277	182	565	3,999	0	7,042	1,185
b. Engines Converted To This Model	0	0	90	2	1,603	1	5,514
c. Engines Reassigned From Other Engine Programs To This Model	0	0	0	8	0	48	27
d. Engines Converted To Other Models	0	90	2	1,604	11	5,514	3
e. Engines Reassigned From This Model To Other Engine Programs	0	0	4	166	2	116	130
f. Engines Scrapped/Lost/Retired	113	68	597	1,291	117	722	145
g. Total Engines Now In This Model	164	24	52	948	1,473	739	6,448
h. Average Age Since New (Hrs.)	2,778	1,423	1,917	1,917	2,147	759	1,254
i. Average Age Since Major O/H (Hrs.)	706	1,377	678	526	285	388	308
j. Age Since New of Oldest Engine (Hrs.) (Includes Hrs. on Engines Converted From Other Models)	4,706	2,051	3,716	4,318	4,258	2,175	5,424
k. Accumulative Engine Flying Hours	620,300	179,400	1,132,000	6,689,600	770,200	6,436,500	3,812,300
l. Initial Shipment Date	3/59	2/60	6/61	8/63	10/68	8/66	4/70

Source: Reference [18A, p. 20].



Source: Reference [18A, p. 22].

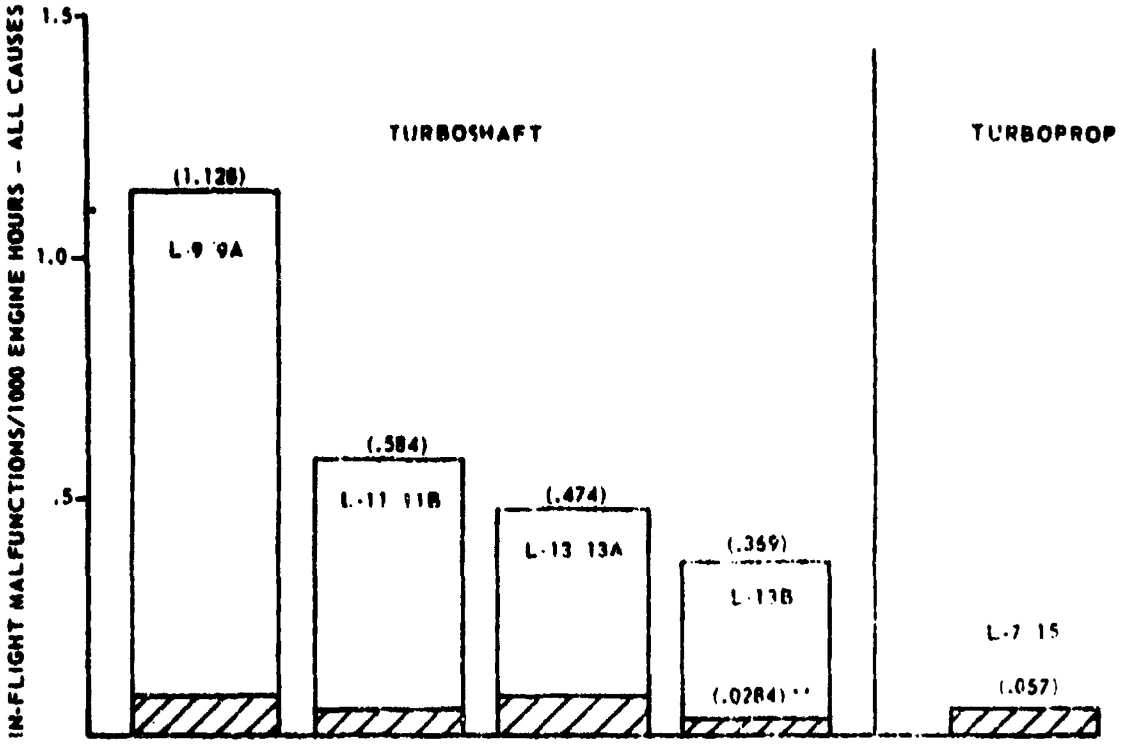
Figure 65. T53 CUMULATIVE FLYING-HOURS



ACTUAL VALUE FOR THE T53-L-13B IN THE R&M OPERATIONAL SAMPLE IS 0.0000 PER 1000 ENGINE FLYING HOURS. HOWEVER THE POINTS SHOWN FOR THE L-13B ARE DERIVED BY USING 50% CONFIDENCE LEVEL ESTIMATE OF FAILURE RATE.

Source: Reference [18A, p. 60].

Figure 66. RELEVANT ENGINE FAILURES - IN-FLIGHT INCIDENTS AND MISSION COMPLETION



* "ALL CAUSES" INCLUDES BOTH ENGINE CAUSES AND ALL OTHER NON-ENGINE CAUSES (FOD, OPERATOR ERROR, ETC.)

** ACTUAL VALUE FOR THE T53-L-13B IN THE R&M OPERATIONAL SAMPLE IS 0.0000 PER 1000 ENGINE FLYING HOURS. HOWEVER THE POINT SHOWN FOR THE L-13B IS DERIVED BY USING 50% CONFIDENCE LEVEL ESTIMATE OF FAILURE RATE.

ENGINE CAUSES

ALL OTHER CAUSES

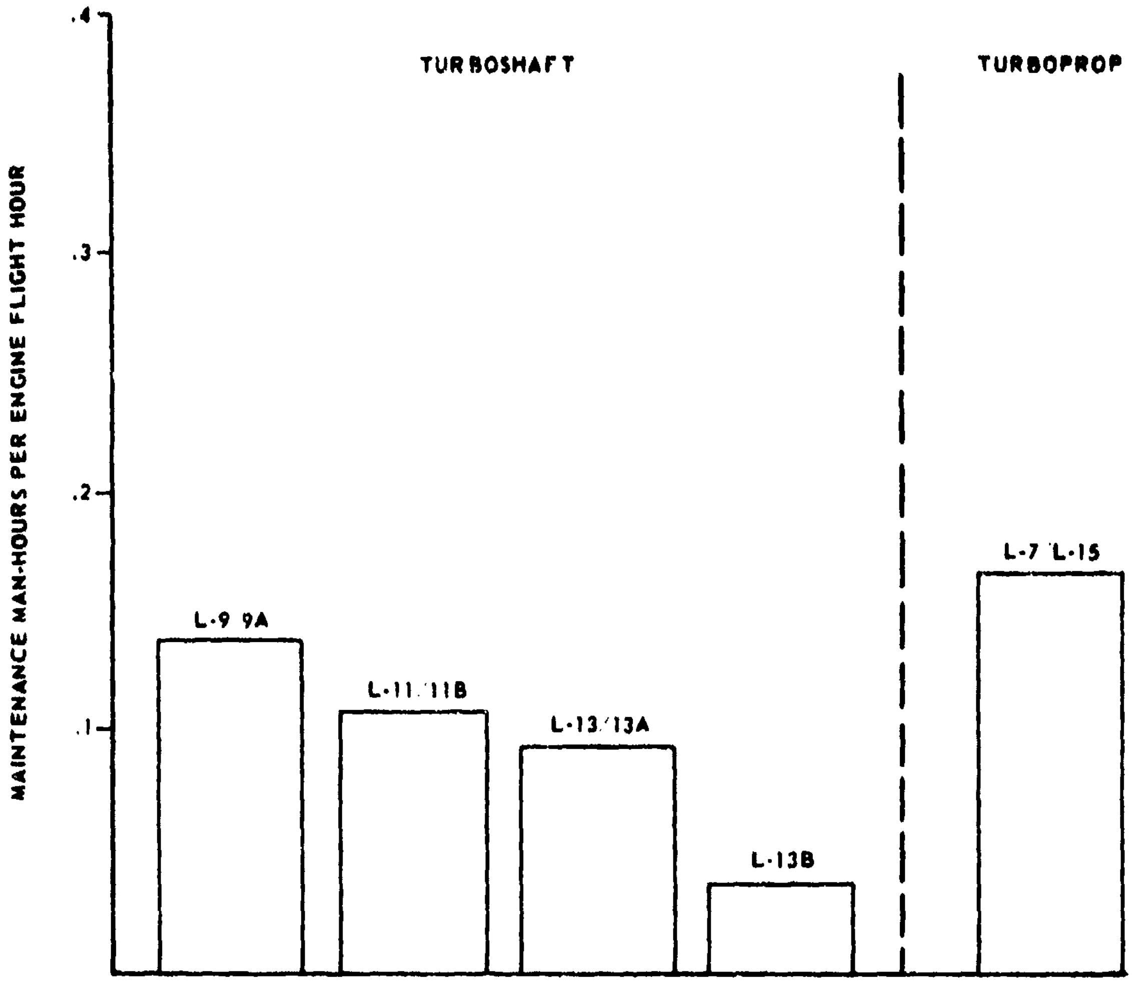
Source: Reference [18A, p. 61].

Figure 67. T53 IN-FLIGHT ENGINE MALFUNCTIONS - ALL CAUSES*

shows the cumulative flying-hours. The turboshaft models are those that are used in helicopters. Figures 66-68 present relevant engine-failure[1] rates, malfunction[2] rates, and MMH/FH,

[1]A relevant engine failure is an engine malfunction, the cause for which has been determined to be the responsibility of the engine manufacturer and attributable to the existence of discrepancies in the engine, its components, or the documentation of its design or use.

[2]A malfunction denotes inability to meet specified operating requirements. A malfunction can occur only during actual operation of the engine; it may or may not constitute a failure.



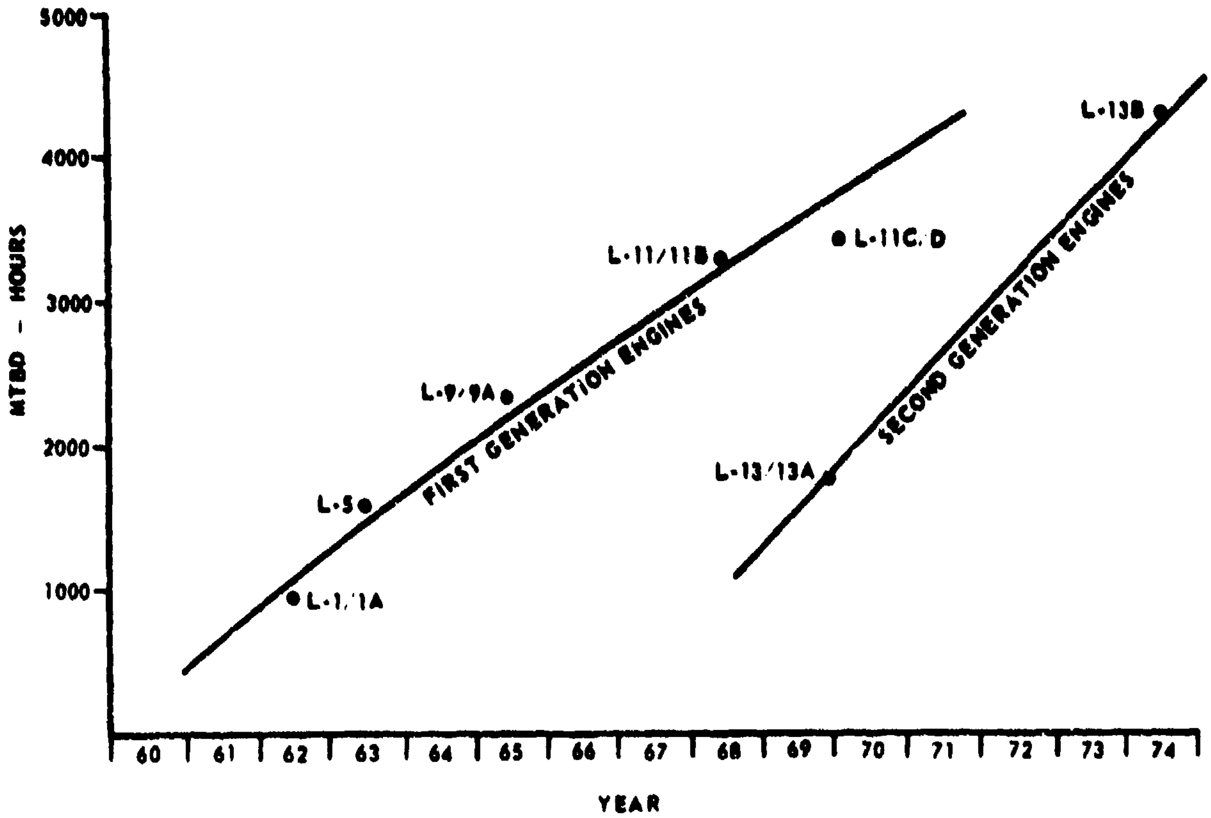
NOTE: MAINTENANCE MAN-HOURS INCLUDE ORGANIZATIONAL AND DIRECT SUPPORT ENGINE MAINTENANCE DUE TO ALL CAUSES, EXCEPTING ROUTINE SCHEDULED EXTERNAL INSPECTIONS.

Source: Reference [18A, p. 72].

Figure 68. T53 MAINTENANCE MAN-HOURS PER ENGINE FLIGHT-HOUR

respectively, for the various T53 engine models. Figure 69 shows the achievement in Mean-Time Between Depot Return (MTBD)[1] for engine causes for the T53 turboshaft family of engines over

[1]The mean time between necessary depot actions for engine causes is calculated by dividing the total flying hours by the total number of engine-caused, necessary, depot removals for the same calendar time period.

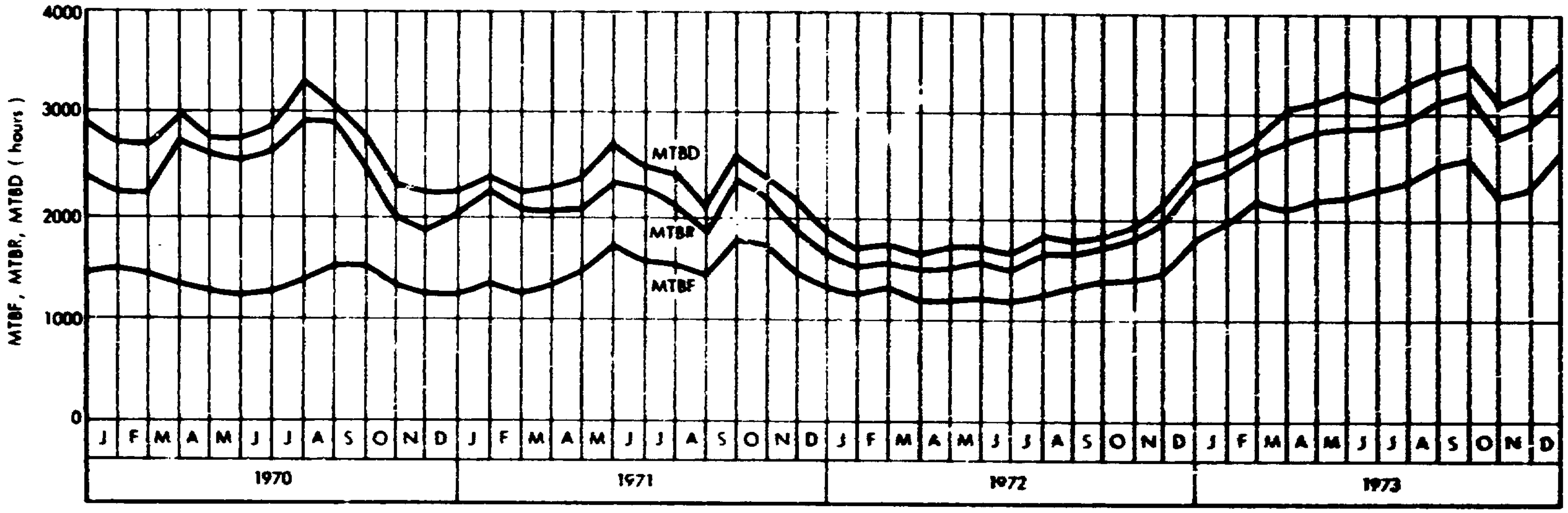


Source: Reference [18A, p. 145].

Figure 69. T53 TURBOSHAFT MTBD - ENGINE CAUSES

the years. All these figures indicate that the successive T53 engine models generally exhibited R&M characteristics improved over earlier models. At the same time, the power rating was being increased in the successive models.

Figure 70 shows reliability trends for all T53 turboshaft engines from 1970 to 1973. Though the reliability measures fluctuated markedly, there was no definite overall trend upwards or downwards over this period of time. The fluctuations were probably due mainly to the mix of different models over time. Table 39 indivates that in addition to new engines, large numbers of engines were sometimes converted to later models. For example, 5,514 engines were converted to the L-13B model configuration,



MTBF - ENGINE MEAN TIME BETWEEN RELEVANT ENGINE FAILURE.
MTBR - MEAN TIME BETWEEN NECESSARY ENGINE-CAUSED REMOVALS FROM AIRFRAME.
MTBD - MEAN TIME BETWEEN NECESSARY DEPOT ACTIONS FOR ENGINE CAUSES.
NOTE: THREE-MONTH MOVING AVERAGES USED FOR SMOOTHING PURPOSES.

SOURCE: REFERENCE [27].

2-3-75-2

Figure 70. MEAN TIME BETWEEN FAILURE, REMOVAL FROM AIRFRAME, AND RETURN TO DEPOT (WORLDWIDE) FOR ALL T53 TURBOSHAFT ENGINES

which was initially shipped in April 1970. Figure 69 indicates that this model had a much greater MTBD than earlier models; the increase in MTBD in Figure 70 from 1972 to 1973 probably reflects an increase in the relative number of L-13B conversions in the inventory.

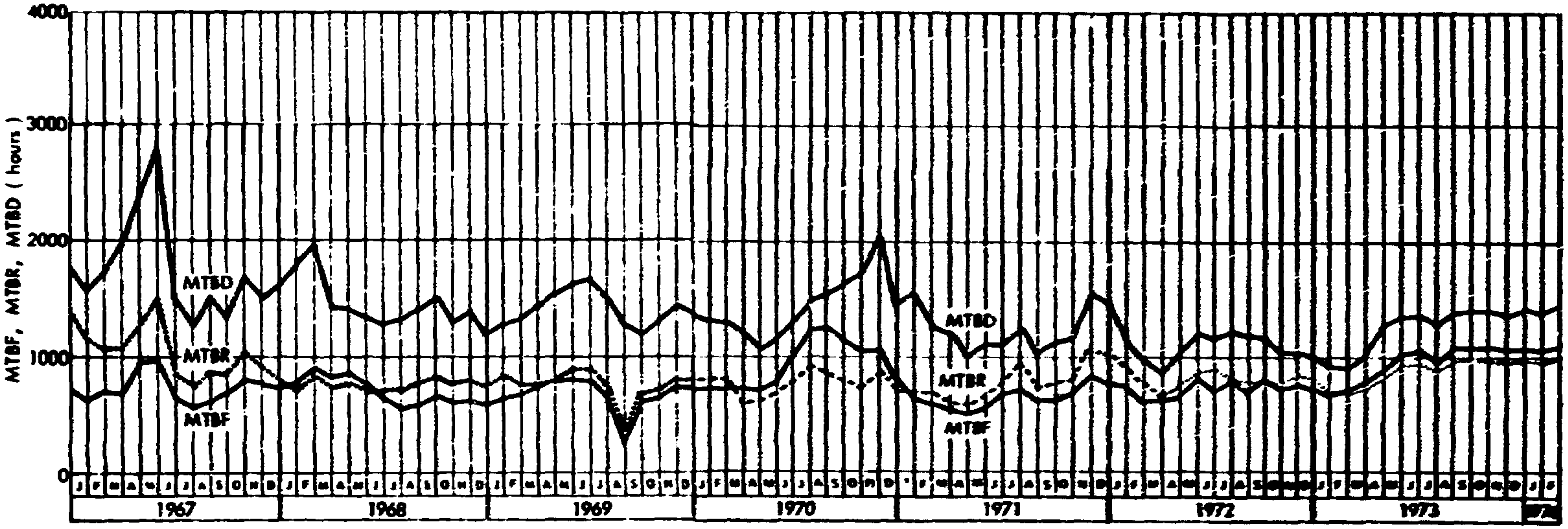
Figures 71 and 72 show approximately constant reliability trends for the T55-L-7/7B/7C engines; unfortunately, we do not have data for other T55 engine models.

The most important reliability measure in these figures is MTBD, which reflects both scheduled and unscheduled depot actions for engine causes; depot actions (many of which are overhauls) are much more costly than nondepot actions. Lycoming personnel stated that depot overhauls account for about 90 percent of total engine-maintenance costs.

It is interesting to note that there is a great difference between the MTBFs (based on ***relevant*** failures) reported by Lycoming for the T53 engines and the MTBFs for these engines obtained from service data (based on *all* failures). For example, Figure 72 for the T53 engine shows MTBF in excess of 1,200 hours from 1970 through 1973. However, Tables 8 and 10 indicate that power-plant MTBF for the H-1 family of aircraft, which use the T53 engine, averaged only about 30 hours between 1968 and 1973. The Lycoming MTBF is based on ***relevant*** engine failures, while the data reported for the helicopter power plants include *all* failures. Lycoming defines a relevant engine failure as

> an engine-malfunction, the cause for which has been determined to be the responsibility of the engine manufacturer and attributable to the existence of discrepancies in the engine, its components, the documentation of its design or use.

Evidently, most T53 engine failures were classified by Lycoming as nonrelevant.



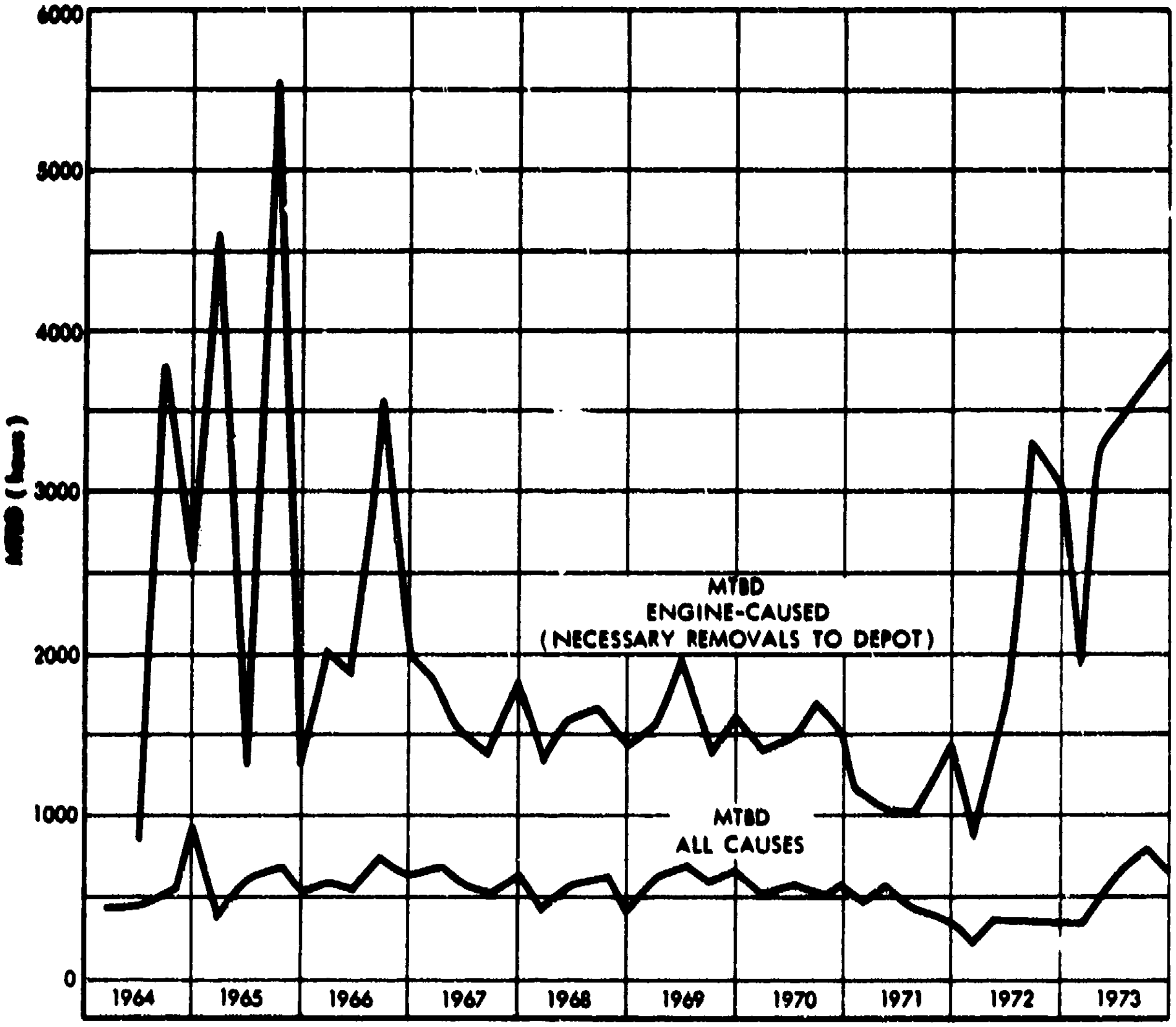
MTBF - ENGINE MEAN TIME BETWEEN RELEVANT ENGINE FAILURE.
MTBR - MEAN TIME BETWEEN NECESSARY ENGINE-CAUSED REMOVALS FROM AIRFRAME.
MTBD - MEAN TIME BETWEEN NECESSARY DEPOT ACTIONS FOR ENGINE CAUSES.

NOTES: (1) THREE-MONTH MOVING AVERAGES USED FOR SMOOTHING PURPOSES
(2) T55-L-11/11A DATA NOT INCLUDED ON THIS FIGURE

SOURCE: FOR 1967-71, REFERENCE [19];
FOR 1970-74, REFERENCE [20].

7-22-74-4

Figure 71. MEAN TIME BETWEEN FAILURE, REMOVAL FROM AIRFRAME, AND RETURN TO DEPOT (WORLDWIDE) FOR THE T55-L-7/7B/7C ENGINES



SOURCE: REFERENCE [21, p. 45]

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Figure 72. MEAN TIME BETWEEN DEPOT REMOVAL FOR THE T55-L-7/7B/7C ENGINES

Chapter V

ANALYSIS OF DATA FROM HELICOPTER MANUFACTURERS

A. BOEING VERTOL

Part A of Volume 2 presents helicopter R&M data (obtained under subcontract from the Boeing Vertol Company), most of which were for the H-46 and CH-47 programs. Most of the H-46s were cargo helicopters operated by the Marine Corps (mainly CH-46As, CH-46Ds, and CH-46Fs). The Navy operated a small number of UH-46As. In addition to these U.S. military aircraft, versions of the H-46 family were operated by New York Airways, the Canadian Army and Air Force, the Swedish Navy and Air Force, and Japanese military and commercial services. First operations were by New York Airways--starting in July 1962. The first flight of the CH-46A was in October 1962, and the aircraft entered field service with the Marine Corps in November 1964 (Reference [24]). Figure 73 shows cumulative flight-hours versus calendar time for the H-46 family of aircraft.

The CH-47A was developed for the U.S. Army and first flew in September 1961. Operating the CH-47A, B, and C models, the Army was for many years the only operator of the CH-47. Starting in 1972, deliveries were made to the military services of Spain, Australia, Italy, Iran, and Candada [25]. Figure 74 shows cumulative flight-hours versus calendar time for the U.S. Army CH-47 family. The Army was the only operator of CH-47s for the first million flight-hours (the period covered by Figure 74).

In order not to introduce transcription errors into the data, Part A is reproduced in the original Boeing format and

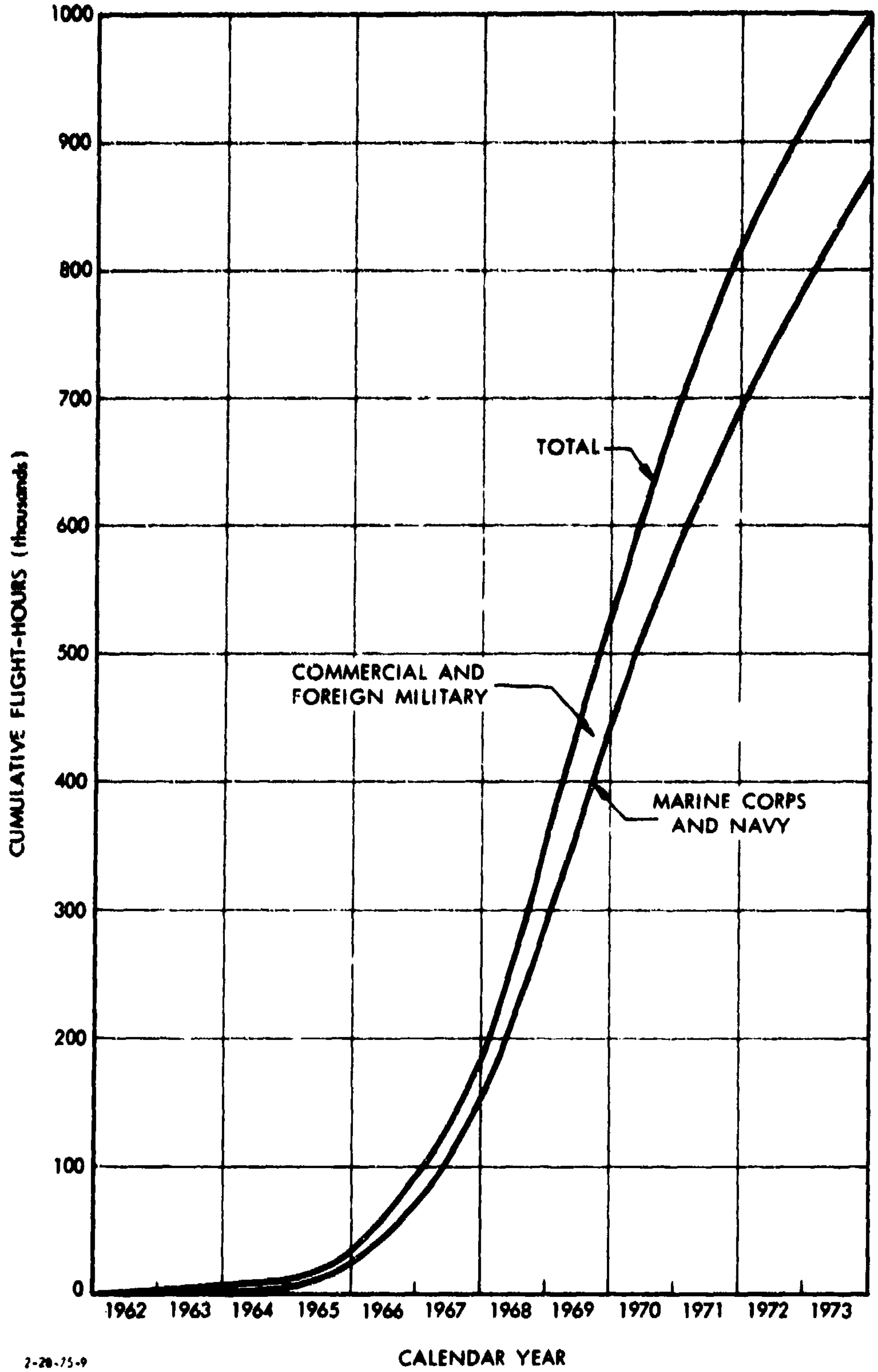


Figure 73. H-46 FLIGHT-HOURS

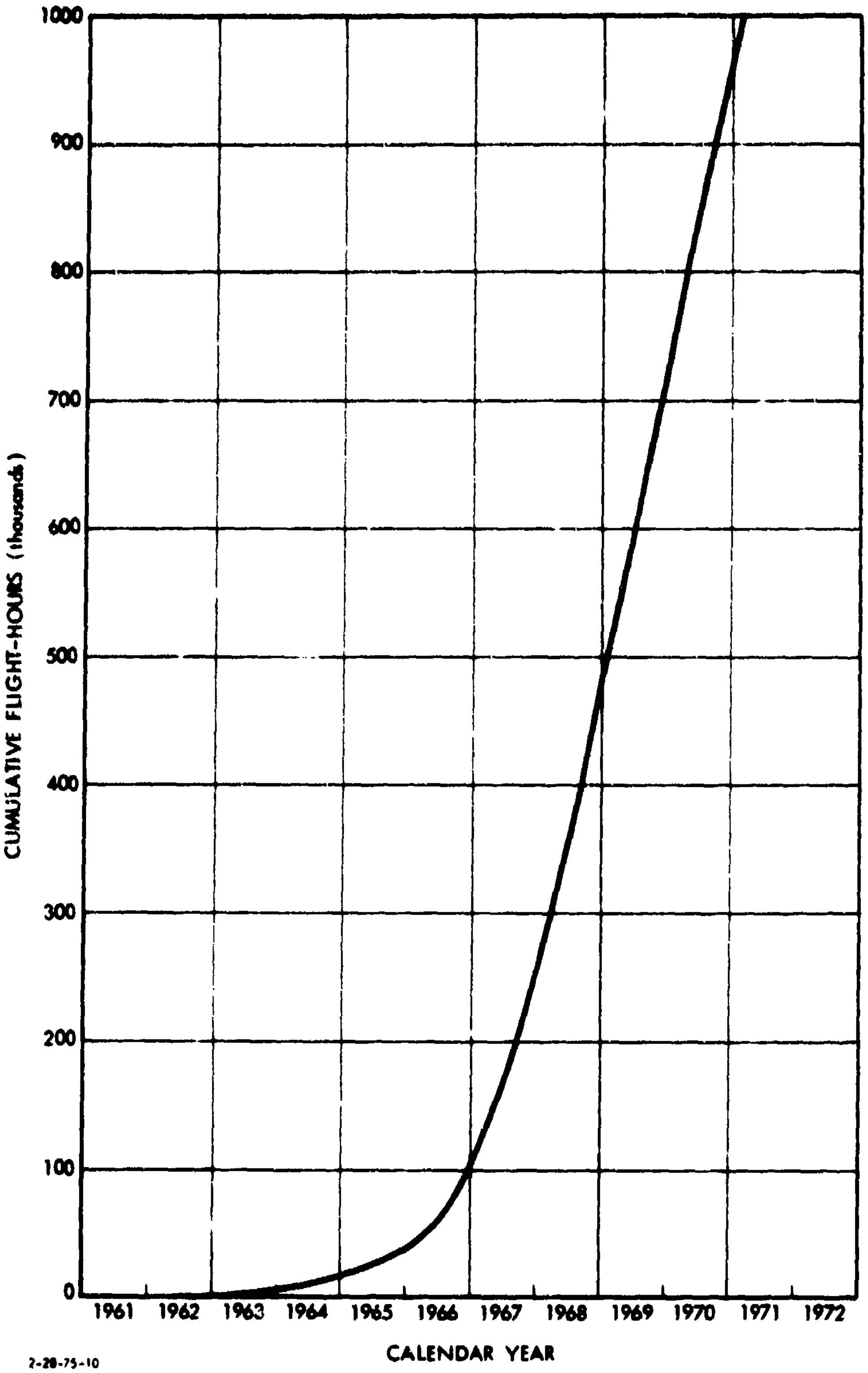


Figure 74. CH-47 FLIGHT-HOURS

is discussed below. Table and figure numbers refer to those of Volume 2, Part A; and items are discussed in the order that they appear there.

CH-47 Reliability. The top panel of Table 1 presents malfunctions per flight-hour for the complete CH-47 and for the total subdivided into 11 systems. Data for the total aircraft are available from 1963 to 1972; data by system are given from 1965 to 1972. The very early phase of operations is not included in these data; cumulative flight-hours were 4,750 in 1963 and 37,033 in 1965. Cumulative malfunction rates are plotted in Figures 1 to 12. At the bottom of each plot, the α (the same as the α used in Duane's and in General Electric's RPM reliability-growth models, but with a change in sign [26]) is given; a negative α indicates reliability growth, while a positive α indicates reliability degradation. The α's for each system and for the total aircraft are summarized in the right panel of Table 2. Note that the total aircraft-reliability growth was quite low (-0.063). The system α's ranged from -0.315 (flight control) to +0.160 (drive). Nine systems exhibited reliability growth, while two exhibited reliability degradation.

CH-47 Maintenance Man-Hours. The bottom panel of Table 1 presents MMH/FH for the complete CH-47 and for the total subdivided into 11 systems. Data are available from 1965 to 1972. The cumulative MMH/FH rates are plotted in Figures 13-24. The α's for each system and for the total aircraft are summarized in the left panel of Table 2. The total aircraft maintenance-improvement growth (i.e., reduced MMH/FH) was -0.172; all of the systems showed maintenance-improvement growth, ranging from -0.415 (equipment) to -0.005 (rotor).

Safety Growth Statistics. Tables 3 to 3-16 present major accident rates for the following helicopters: UH-1(Army),

UH-1(Navy/Marine Corps), H-2(Navy), H-3(Navy), OH-6(Army), H-19(Navy), H-19(Army), H-21A/B(Air Force), H-21C(Army), H-34 (Army), H-34(Navy/Marine Corps), H-37(Navy), CH-37(Army), UH/CH-46, CH-47, CH-53(Marine Corps), and CH-54(Army). For the CH-46 and CH-47, the data were from Boeing Vertol records for all years. For all the other aircraft, the data through CY 1968 were from Vertol records; the data for FYs 1968-73 were obtained by IDA from the Naval Safety Center and the U.S. Army Agency for Aviation Safety. For those helicopters with operations spanning both periods, the IDA data have been added to the Boeing Vertol data to provide more complete coverage. The cumulative accident rates have been plotted for all the helicopters in Figure 25 and by individual helicopter type in Figures 26-42. The α's for each helicopter type are summarized in Table 4. Fifteen of the 17 helicopter types exhibit safety-reliability growth. Only the UH-1(Navy/Marine Corps) and the H-21C(Army) show safety degradation. The α's for the 17 types range from -0.742 for the H-19(Army) to +0.158 for the H-21C(Army). The average value of α for all 17 helicopter types was -0.23.

CH-46 Reliability. Table 5 presents malfunctions per flight-hour for the complete CH-46 and for the total subdivided into 23 systems. Data are available for the 23 systems only for 1968, 1969, 1970, and 1972. Data for the complete helicopter are available for these years, as well as for 1962-67. Cumulative flight-hours were 10,000 in 1962 and 394,000 in 1968. The reliability of the total helicopter improved markedly, from 2.00 malfunctions per flight-hour in 1962 to 0.723 in 1968; by 1972, however, it worsened to 0.925 malfunctions per flight-hour. The cumulative malfunction rates are plotted in Figures 43-66; the α's for each system and for the total aircraft are summarized in the right panel of Table 7. Because of its reliability growth from 1962 to 1968, the total aircraft exhibits good reliability growth (α = -0.218). The system α's in general show a slight reliability degradation from 1968 to 1972. The

system α's ranged from -0.372 (airframe) to +0.547 (miscellaneous utilities). Nine systems exhibited reliability growth, while 14 exhibited reliability degradation. The average value of α for all 23 systems from 1968 to 1972 was 0.089. Based on all CH-46 operations, these system trends from 1968 to 1972 are generally consistent with the 3-M data, excluding Pacific Theater (Vietnam) operations. Figure N-20 indicates that MTBF for the five major systems worsened between 1968 and 1972.

CH-46 Maintenance Man-Hours. Table 6 presents MMH/FH for the complete CH-46 and for the total subdivided into 23 systems. Data are available only for 1968, 1969, 1970, and 1972. The cumulative MMH/FH rates are plotted in Figures 67-90; the α's for each system and for the total aircraft are summarized in the left panel of Table 7. The MMH/FH for the total aircraft worsened (increased) slightly (α = 0.010). The system α's ranged from -0.288 (airframe) to +0.410 (fuselage compartment). Eight systems exhibited maintenance improvement (reduced MMH/FH), while 15 exhibited maintenance degradation (increased MMH/FH). These system trends from 1968 to 1972, based on all CH-46 operations, do not show as much degradation in MMH/FH as the 3-M data excluding Pacific Theater (Vietnam) operations. Figure N-21 indicates that MMH/FH for four of the five major systems worsened between 1968 and 1972.

H-21 Maintenance Man-Hours. Figure 91 shows MMH/FH for H-21 helicopters of the French Army during the Algerian War. Data for these helicopters were carefully reported by service representatives because these were the first Boeing Vertol helicopters engaged in combat operations. When the H-21 entered French Army service, it had already accumulated about 70,000 flight-hours in U.S. Army and Air Force service (see Table 3-7). Figure 91 indicates that MMH/FH increased as the aircraft aged and reached a rather stable level after a year. This is a typical pattern following introduction of a helicopter into service. While the

aircraft are new, maintenance requirements are relatively low; as they accumulate flight time, components reach their overhaul time and other parts of the helicopter require more maintenance. After a year or so, the level of maintenance tends to stabilize as improvements to the aircraft tend to offset the adverse effects of aging.

CH-47 Transmission Reliability. Table 8 presents unscheduled removal rates for the four transmissions of the CH-47. Both yearly and cumulative removal rates are plotted in Figures 92-99 and corresponding α's are shown in Table 10. There was reliability growth for all four transmissions; α's based on cumulative removal rates ranged from -0.450 to -0.041. The average value of α for all four transmissions was -0.22.

Figures 75-78 (on the next four pages, not in Volume 2) show TBO histories for four models of the CH-47. The TBOs for the four transmissions increased over time in all CH-47 models, and each achieved a TBO of 1,200 hours. Since TBOs determine scheduled removal rates, both the unscheduled and scheduled removal rates for all transmissions exhibit reliability growth.

CH-47 Component Reliability. Table 9 presents unscheduled removal rates for major CH-47 components that are overhauled when they fail. Both yearly and cumulative removal rates are plotted in Figures 100-115, and corresponding α's are shown in Table 11. α's based on cumulative removal rates ranged from -0.334 to +0.632. Five components exhibited reliability growth, while three exhibited reliability degradation. However, the average value of α was 0.019, indicating slight reliability degradation.

Tables B-1 to B-4 include TBO histories for four of the components of Tables 9 and 11 (pivoting actuator, swiveling actuator, rotor blades, and swashplates). In all cases except for the CH-47B rotor blades, the TBOs either increased or remained constant. The TBO of the CH-47B rotor blades decreased

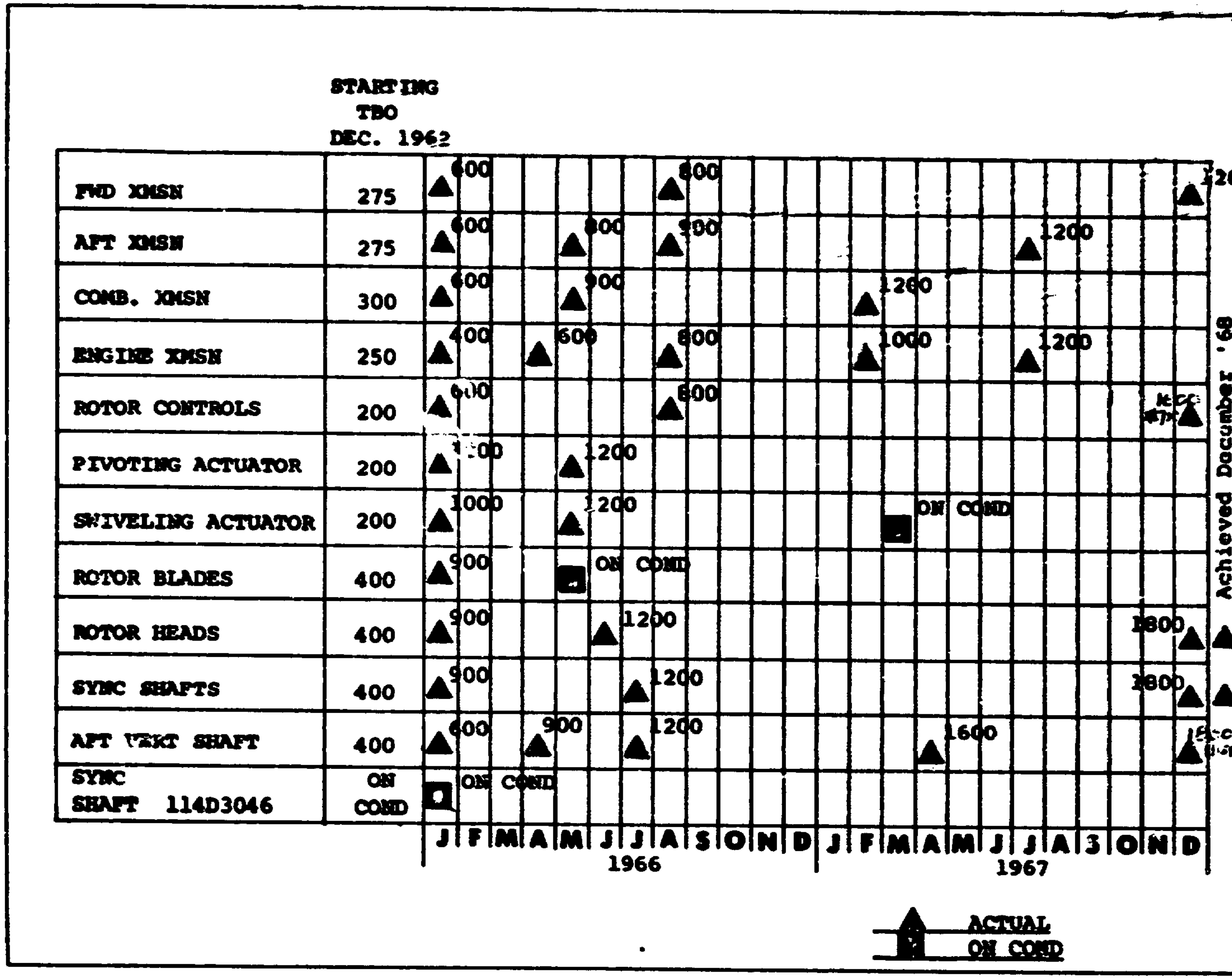


Figure 75. CH-47A COMPONENT SCHEDULE

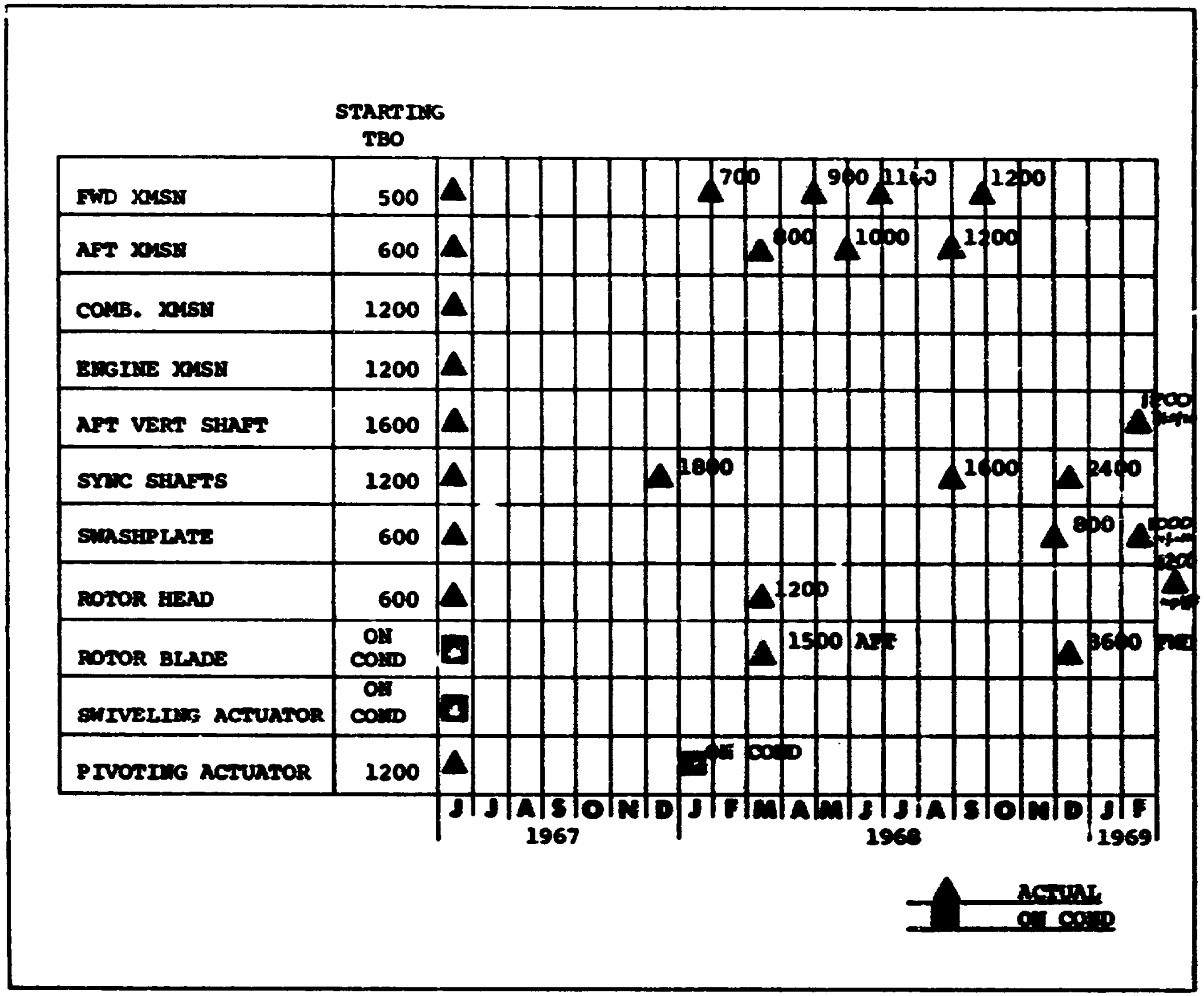


Figure 76. CH-47B COMPONENT SCHEDULE

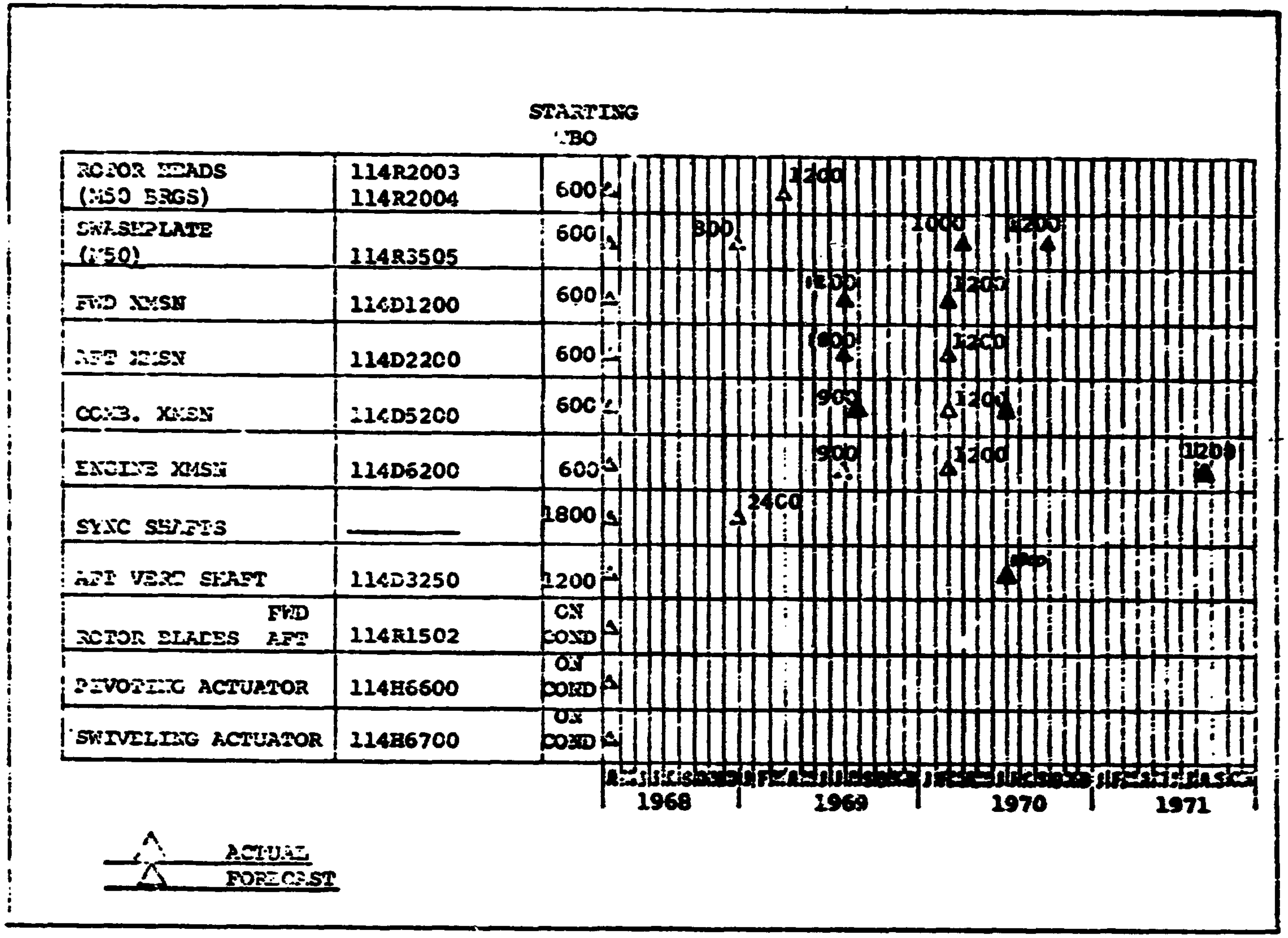


Figure 77. CH-47C COMPONENT SCHEDULE, WITH L7C ENGINES

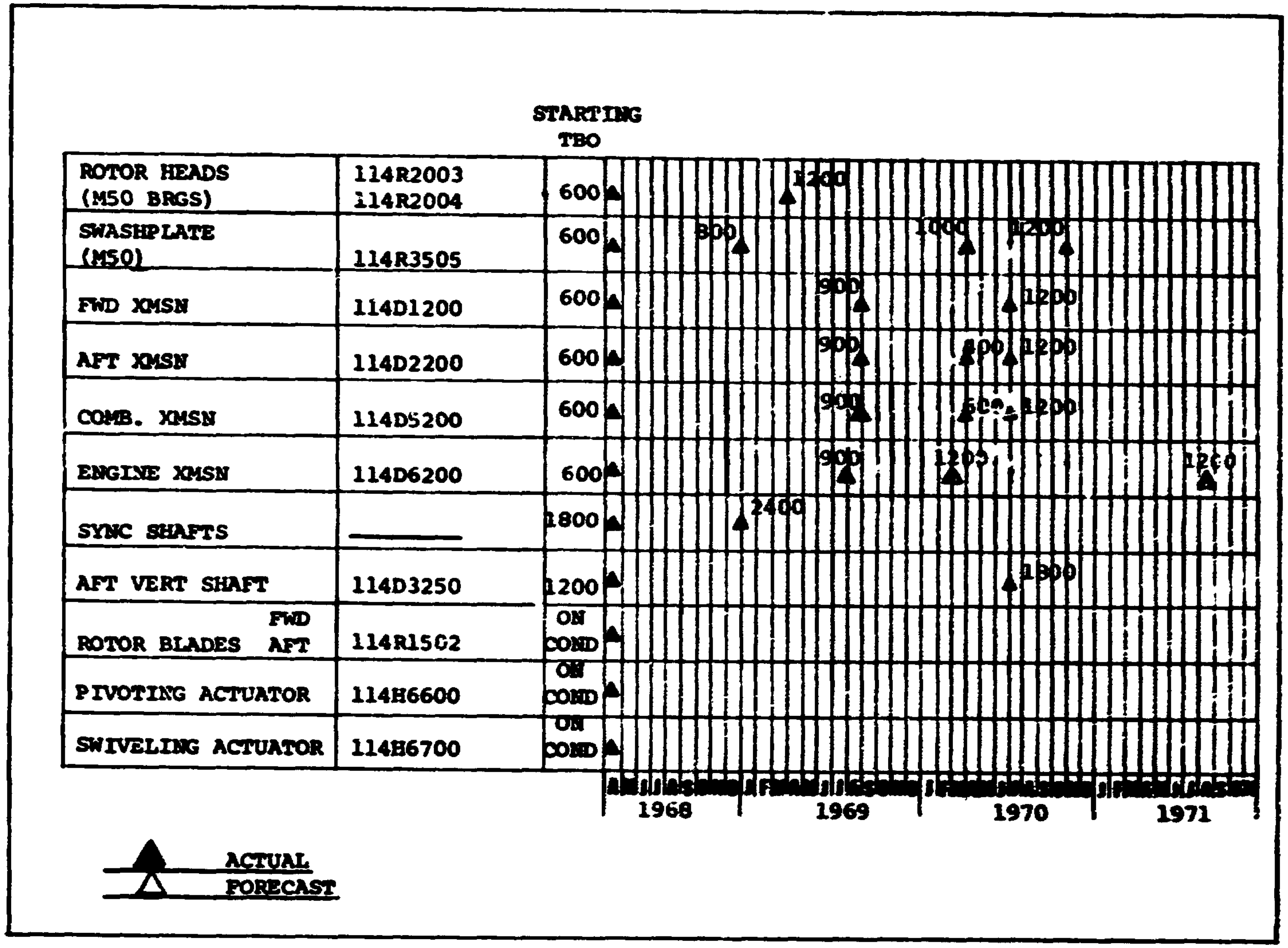


Figure 78. CH-47C COMPONENT SCHEDULE, WITH L11 ENGINES

from "On Condition" to 1,500 hours for the aft rotor and 3,600 hours for the forward rotor. The TBO of the CH-47A blades increased from 400 hours to "On Condition," and the TBO of the CH-47C blades was always "On Condition." Hence the trend in scheduled (TBO) removal rate for rotor blades was mixed, while the unscheduled removal rate worsened ($\alpha = 0.146$). For the other three components, both the scheduled (TBO) and unscheduled removal rates improved.

CH-46 Component Reliability. Table 12 presents unscheduled removal rates for CH-46 transmissions and rotor heads. Both yearly and cumulative removal rates are plotted in Figures 116-125, and corresponding α's are shown in Table 13. α's based on cumulative removal rates ranged from -0.284 to +0.709. Two components exhibited reliability growth, while three exhibited reliability degradation. The average value of α for all five components was 0.14--indicating slight reliability degradation. Interestingly, the aft transmission and rotor head showed improvement, while the forward transmission and rotor head showed degradation.

Helicopter Maintenance Trends. Figure 126 shows the trends of helicopter and fixed-wing direct-maintenance costs versus weight empty (W.E.). The helicopter direct-maintenance cost increases with $(W.E.)^{0.7}$. The insert indicates a rather weak relationship between maintenance cost and year of introduction.

Figure 127 shows a trend of MMH/FH versus W.E. As would be expected, MMH/FH increases with W.E. Using the equation fitted through the points of Figure 127, Figure 128 normalizes for W.E. and shows the effect of year of introduction on MMH/FH. Figure G-2 indicates that, for equal W.E., MMH/FH has been decreasing with year of introduction. This decrease will tend to flatten out in the future, as successive generations of helicopters are introduced (MMH/FH can not be negative).

B. HUGHES

Part B of Volume 2 presents R&M data (obtained under subcontract from Hughes Helicopters) for the YOH-6 and OH-6A helicopters. In order not to introduce transcription errors into the data, Part B is reproduced in the original Hughes format and is discussed below.

Ten prototype YOH-6 aircraft were built and had first flight dates from 27 February 1963 to 30 April 1964. These aircraft were flown in various tests at many scattered locations in CONUS. First production-aircraft flying started in May 1966. (More detailed program history is given in Volume 2, pp. H-1 - H-5.)

Figure 79 summarizes the failure and removal data provided in Part B. The blocks indicate the periods of time covered for each of the seven sets of data. Failure data are broken down into the following subsystem categories: (1) rotors, (2) airframe, (3) transmissions and drives, (4) power plant, (5) instruments and electrical, (6) communications, and (7) weapon systems. Failure data are presented for Subsystems (1), (2), (3), and (5) in all cases; but, as noted in Figure 79, data for Subsystems (4), (6), and (7) are not always presented. In some cases, the contractor-furnished equipment (CFE) associated with the power plant subsystem is included, but the government-furnished equipment (GFE) is not included. The GFE is the engine itself.

In addition to the failure data, Volume 2 includes "Total Removals" for all aircraft except Prototype No. 6 (p. H-16) and the nine production aircraft (p. H-24). The number of removals refer to the removal of all major components for overhaul or repair. Both failures and removals are categorized as "Chargeable" (C) or "Non-Chargeable" (NC). Chargeable failures or removals are those caused by some deficiency in the item itself that caused its failure or removal, while nonchargeable failures or removals are due to some other cause (e.g., a maintenance

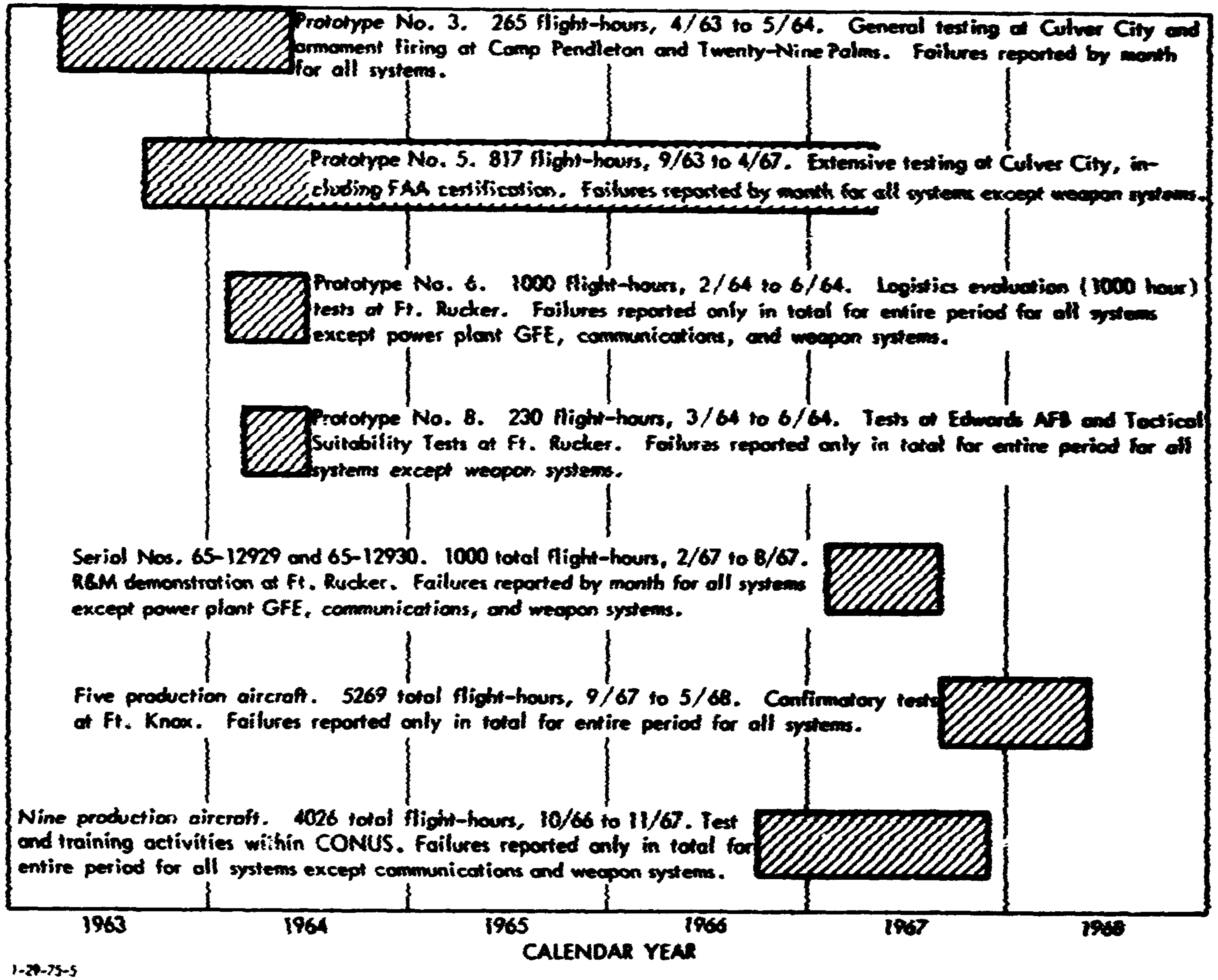


Figure 79. OH-6A FAILURE AND REMOVAL DATA PROVIDED BY HUGHES

error committed by a mechanic). Because the assignment of cause to "chargeable" or "nonchargeable" often involves subjective judgment, we have used the sum of both chargeable and nonchargeable failures and removals in all our analyses. The sum of both categories should provide a truer picture of total reliability growth than the use of only chargeable failures or removals.

Because of the incomplete failure reporting of Subsystems (4), (6), and (7), we have not used them in our analysis of reliability growth. Table 40 summarizes the failure data for the other four subsystems, as well as the total removal data.

The data of Table 40 cover a total of 12,607 flight-hours from April 1963 to May 1968 for 20 aircraft. Other aircraft were also accumulating flight-hours over this same time period. Figure 80 (based on Hughes' Figure 2-1 [Vol. 2, p. B-5, below]) shows total flight-hours for the entire YOH-6/OH-6A fleet. It indicates approximately 27,000 total fleet flight-hours by May 1968. Hence, the data of Table 40 represents slightly less than half the total fleet flight-hours accumulated by May 1968. In determining growth rates relative to cumulative flight-hours, the data of Table 40 must be related to the total fleet flight-hours, since learning is associated with all the aircraft being flown.

In Table 41, we have accumulated by calendar time from Table 40 the flight-hours, total failures (for the four subsystems of Table 40), and total removals. We have not included the data for Prototype No. 6, which was being flown in a 1,000-hour logistics evaluation at Fort Rucker at the same time Prototype No. 5 was being flown at Culver City. Its reported failure rate was only about one-third that of No. 5, as well as much lower than that of Prototypes Nos. 3 and 8 (see Vol. 2, p. B-7, below). It is highly probable that its failure reporting was not complete, and for that reason it was not included in the

Table 40. OH-6A FAILURE AND REMOVAL DATA (CHARGEABLE AND NON-CHARGEABLE FAILURES)

Month	Flight-Hours	Number of Failures					Total Removals
		Rotors	Airframe	Transmissions and Drives	Instruments and Electrical	Total	
Prototype No. 3							
4/63	9.8	2	1	0	0	3	6
5/63	19.9	5	1	1	4	11	8
6/63	12.1	5	0	1	3	9	9
7/63	33.0	5	3	2	1	11	7
8/63	24.5	2	8	3	2	15	8
9/63	23.0	1	3	0	3	7	6
10/63	6.4	1	0	0	0	1	1
11/63	33.8	0	8	1	0	9	8
12/63	25.5	1	5	0	3	9	11
1/64	20.8	0	1	1	2	4	3
2/64	18.1	0	1	0	0	1	2
3/64	13.7	0	2	0	0	2	2
4/64	17.2	1	3	1	1	6	7
5/64	6.8	0	0	1	0	1	1
Total	264.6					89	79
Prototype No. 5							
9/63	4.5	1	5	3	3	12	2
10/63	21.7	9	5	6	2	22	11
11/63	26.5	5	3	0	2	10	10
12/63	5.0	5	7	2	2	16	17
1/64	55.8	8	16	0	4	28	14
2/64	33.9	3	7	2	4	16	12
3/64	17.0	2	7	1	6	16	11
4/64	22.0	3	8	0	0	11	6
5/64	49.5	5	7	1	1	14	14
6/64	112.7	4	4	0	7	12	18
7/64	38.2	2	7	0	7	16	15
8/64	24.3	2	6	0	0	8	4
9/64	26.6	3	13	2	4	22	9
10/64	1.4	1	1	0	0	2	1
11/64	18.4	3	2	1	0	6	4
12/64	10.9	1	1	1	0	3	1
1/65	6.1	0	1	0	1	2	0
2/65	1.2	0	2	0	0	2	1
3/65	34.0	1	2	0	2	4	2
4/65	23.2	0	3	0	1	4	2
5/65	3.9	1	0	1	1	3	3
6/65	4.1	0	0	0	1	1	0

(continued on next page)

Table 40 (continued)

Month	Flight-Hours	Number of Failures: Rotors	Airframe	Transmissions and Drives	Instruments and Electrical	Total	Total Removals
Prototype No. 5 (contd)							
7/65	9.2	2	1	0		3	1
8/65	15.5	2	3	1		8	5
9/65	11.1	1	1	1	[illegible]	4	2
10/65	6.4	1	1	0	1	3	0
11/65	9.0	2	3	1	0	6	4
12/65	8.8	2	0	1	3	6	2
1/66	11.2	3	7	1	1	12	4
2/66	28.0	2	1	1	0	4	2
3/66	18.8	1	2	2	1	6	5
4/66	11.8	2	1	0	1	4	3
5/66	25.8	2	1	0	2	5	7
6/66	12.2	3	2	0	1	6	5
7/66	6.0	1	1	0	0	2	0
8/66	4.1	0	1	0	1	2	0
9/66	16.8	1	2	0	0	3	3
10/66	32.5	1	2	0	2	5	3
1[illegible]6	0	1	5	0	1	7	1
12/66	0	0	7	0	0	7	0
1/67	36.6	1	0	0	0	1	0
2/67	1.8	0	0	0	1	1	0
3/67	0	1	8	0	4	13	5
4/67	11.0	1	1	0	2	4	1
Total	817.5					342	210
Prototype No. 6							
2-6/64	1,000	34	40	11	27	112	--
Prototype No. 8							
3-6/64	230	25	28	6	31	90	57
R&M Aircraft, Serial Nos. 65-12929 and -12930							
2/67	36.1	0	0	0	0	0	0
3/67	262.4	8	14	0	9	31	14
4/67	108	5	9	1	5	20	14
5/67	131.6	14	34	3	17	68	31
6/67	255	27	64	10	31	132	66
7/67	96.6	2	18	4	6	30	20
8/67	110.6	4	22	7	10	43	17
Total	1,000.3					324	162

(concluded on next page)

Table 40 (concluded)

Month	Flight-Hours	Number of Failures: Rotors	Airframe	Transmissions and Drives	Instruments and Electrical	Total	Total Removals
Five Confirmatory Aircraft, Serial Nos. 65-12940, -12944, -12946, -12955, -12965							
9/67 - 5/68	5,269	106	298	22	305	731	529
Nine Production Aircraft, Serial Nos. 65-21916, -21917, -21918, -21919, -21921, -21923, -21925, -21926, 21927							
10-12/66 - 10/67	4,026	57	168	40	79	344	--
Grand Total	12,607.4				2,032	2,032	1,037

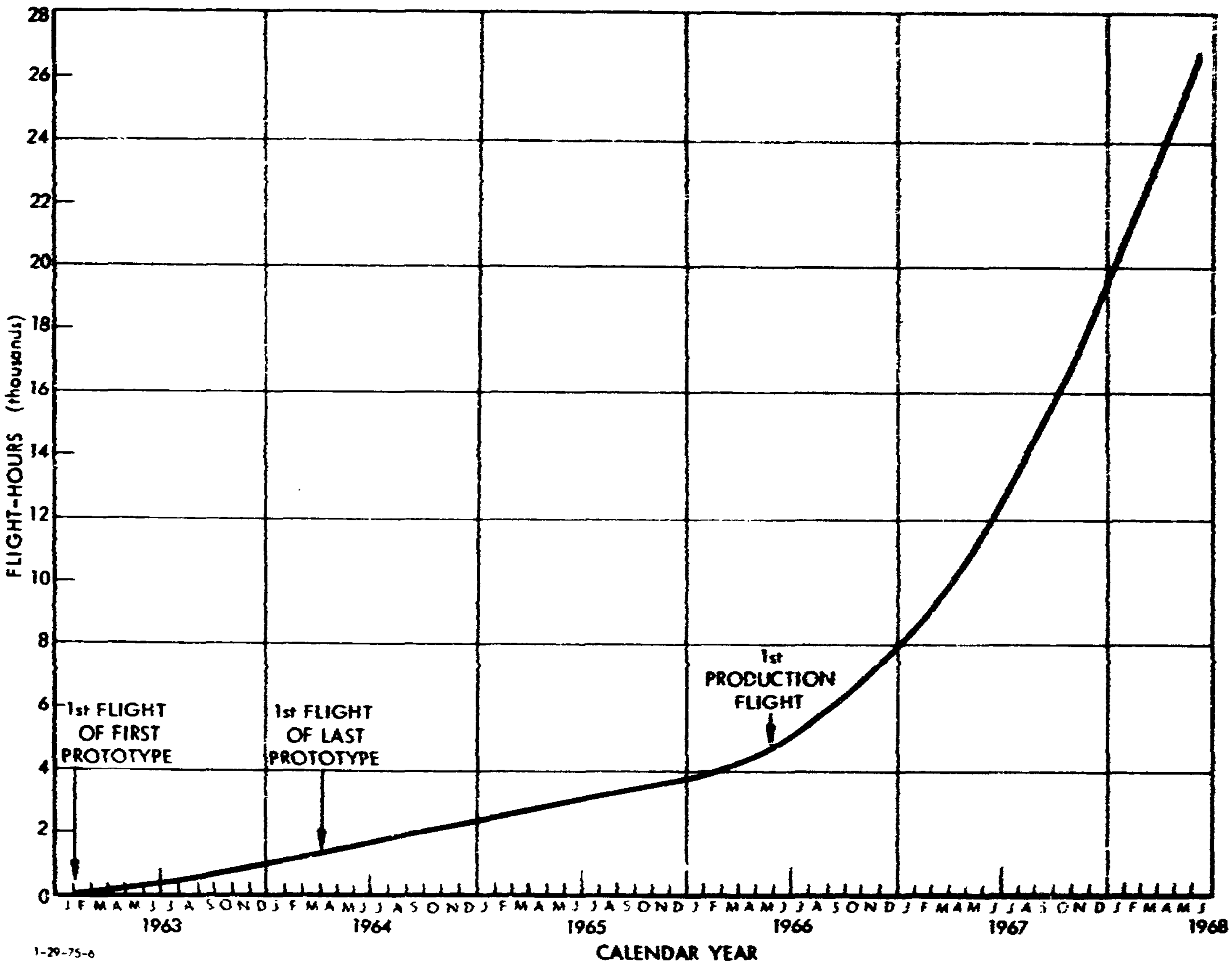


Figure 80. OH-6 TOTAL FLEET FLIGHT-HOURS

Table 41. OH-6 CUMULATIVE FAILURE AND REMOVAL RATES

Month	Flight-Hours			Failures			Removals		
	Number	Cumulative	Total Fleet	Number	Cumulative	Cumulative Rate	Number	Cumulative	Cumulative Rate
4/63	9.8	9.8	100	3	3	.31	6	6	.61
5/63	19.9	29.7	160	11	14	.47	8	14	.47
6/63	12.1	41.8	210	9	23	.55	9	23	.55
7/63	33.0	74.8	300	11	34	.45	7	30	.40
8/63	24.5	99.3	400	15	49	.49	8	38	.38
9/63	27.5	126.8	500	19	68	.54	8	46	.36
10/63	28.1	154.9	600	23	91	.59	12	58	.37
11/63	60.3	215.2	720	19	110	.51	18	76	.35
12/63	30.5	245.7	840	25	135	.55	28	104	.42
1/64	76.6	322.3	980	32	167	.52	17	121	.38
2/64	52.0	374.3	1,110	17	184	.49	14	135	.36
3/64	30.7	405.0	1,240	18	202	.50	13	148	.37
4/64	39.2	444.2	1,390	17	219	.49	13	161	.36
5/64	56.3	500.5	1,560	15	234	.47	15	176	.35
6/64	342.7	843.2	1,720	102	336	.40	75	251	.30
7/64	38.2	881.4	1,900	16	352	.40	15	266	.30
8/64	24.3	905.7	2,050	8	360	.40	4	270	.30
9/64	26.6	932.3	2,220	22	382	.41	9	279	.30
10/64	1.4	933.7	2,390	2	384	.41	1	280	.30
11/64	18.4	952.1	2,560	6	390	.41	4	284	.30
12/64	10.9	963.0	2,720	3	393	.41	1	285	.30
1/65	6.1	969.1	2,890	2	395	.41	0	285	.29
2/65	1.2	970.3	3,060	2	397	.41	1	286	.29
3/65	34.0	1,004.3	3,210	4	401	.40	2	288	.29
4/65	23.2	1,027.5	3,390	4	405	.39	2	290	.28
5/65	3.9	1,031.4	3,550	3	408	.40	3	293	.28
6/65	4.1	1,035.5	3,710	1	409	.39	0	293	.28
7/65	9.2	1,044.7	3,880	3	412	.39	1	294	.28
8/65	15.5	1,060.2	4,020	8	420	.40	5	299	.28
9/65	11.1	1,071.3	4,200	4	424	.40	2	301	.28
10/65	6.4	1,077.7	4,380	3	427	.40	0	301	.28
11/65	9.0	1,086.7	4,550	6	433	.40	4	305	.28
12/65	8.8	1,095.5	4,700	6	439	.40	2	307	.28
1/66	11.2	1,106.7	4,850	12	451	.41	4	311	.28
2/66	28.0	1,134.7	5,020	4	455	.40	2	313	.28
3/66	18.8	1,153.5	5,200	6	461	.40	5	318	.28
4/66	11.8	1,165.3	5,380	4	465	.40	3	321	.28
5/66	25.8	1,191.1	5,530	5	470	.39	7	328	.28
6/66	12.2	1,203.3	5,760	6	476	.40	5	333	.28
7/66	6.0	1,209.3	6,010	2	478	.40	0	333	.28
8/66	4.1	1,213.4	6,320	2	480	.40	0	333	.27
9/66	16.8	1,230.2	6,680	3	483	.39	3	336	.27
10/66	32.5	1,262.7	7,060	5	488	.39	3	339	.27
11/66	0	1,262.7	7,500	7	495	.39	1	340	.27
12/66	0	1,262.7	8,000	7	502	.40	0	340	.27
1/67	36.6	1,299.3	8,550	1	503	.39	0	340	.26
2/67	37.9	1,337.2	9,150	1	504	.38	0	340	.25
3/67	262.4	1,599.6	9,850	44	548	.34	19	359	.22
4/67	119	1,718.6	10,600	24	572	.33	15	374	.22
5/67	131.6	1,850.2	11,450	68	640	.35	31	405	.22
6/67	255	2,105.2	12,400	132	772	.37	66	471	.22
7/67	96.6	2,201.8	13,350	30	802	.36	20	491	.22
8/67	110.6	2,312.4	14,400	43	845	.37	17	508	.22
10/67	4,026	6,338.4	16,610	344	1,189	.19	--*	--*	--*
5/68	5,269	11,607.4*	27,000	731	1,920	.17	529*	1,037*	.14*

*Removal data not available for block of 4,026 flight-hours ending October 1967. Hence, cumulative flight-hours for removal data through May 1968 are 11, 607 - 4,026 = 7,581.4.

calculations of Table 41. Cumulative failure and removal rates are calculated and total fleet flight-hours (from Figure 80) are shown.

In Figure 81 the cumulative failure rate versus the cumulative fleet flight-hours is plotted on log-log paper--the same format Duane used in his reliability growth paper [26]. Figure 75 indicates that the failure rate remained approximately constant at about 0.5 for the first 1,000 hours and then improved after that time. The last two points, reflecting the failure rates of the nine production aircraft and five confirmatory aircraft, lower the cumulative failure rate considerably from that of the prototype aircraft. Possibly, the failure reporting for these production aircraft was not as complete as for the earlier aircraft. However, if we accept the final point as valid and put a trend line from it through the 1,000-hour point, we obtain a rate of growth corresponding in the Duane formulation to $\alpha = 0.35$, which is the maximum α that could be ascribed to these data. It should be remembered that the failure rates of Figure 81 are for only four of the seven subsystems of the aircraft. Table 42 presents the ratios of the numbers of failures for the other three subsystems to those of the four subsystems of Figure 81. Table 42 indicates that the failure rates of Figure 75 should be multiplied by approximately (1 + .29 + .06 + .12 =) 1.47 to obtain the failure rates for the complete aircraft. Accordingly, the cumulative failure rate for the complete aircraft would be about 0.74 for the first 1,000 hours; and then it would reduce to approximately 0.24 at 27,000 hours.

In Figure 82, the cumulative removal rate is plotted versus the cumulative fleet flight-hours. Here, apparently, there was reliability growth over the entire period. As in the case of failure rate, the last point (reflecting the removal rate of the five confirmatory aircraft) lowers the cumulative removal

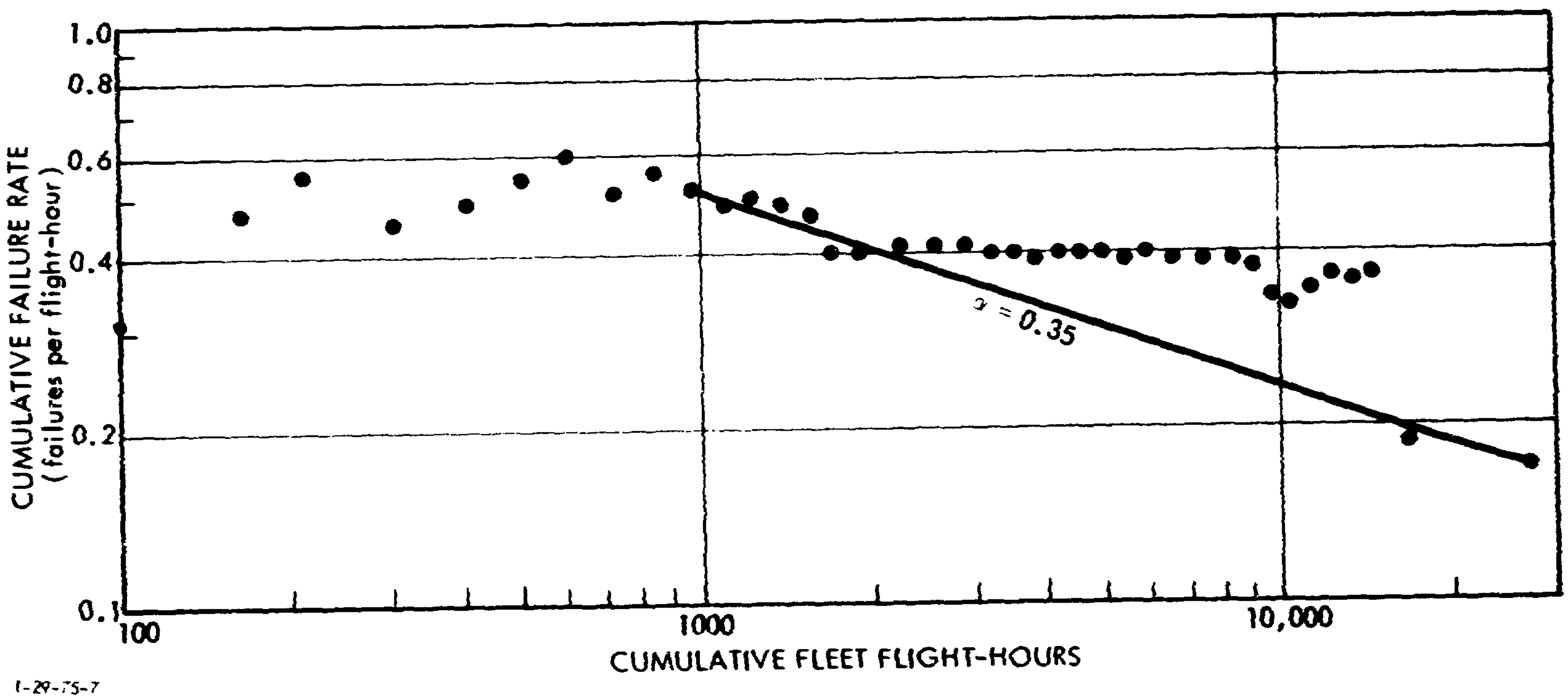


Figure 81. OH-6A CUMULATIVE FAILURE RATE VERSUS CUMULATIVE FLIGHT-HOURS

Table 42. RATIOS OF FAILURES OF POWER PLANT (INCLUDING GFE), COMMUNICATIONS AND WEAPON SYSTEMS TO TOTAL OF ROTORS, AIRFRAME, TRANSMISSIONS AND DRIVES, AND INSTRUMENTS AND ELECTRICAL

Aircraft	Number of Failures				Ratio		
	Power Plant (Including GFE)	Communi-cations	Weapon Systems	Four Other Subsystems	Power Plant (Including GFE)	Communi-cations	Weapon Systems
Prototype No. 3	32	3	1	89	.36	.03	.01
Prototype No. 5	81	10	--	342	.24	.03	--
Prototype No. 6	--	--	--	112	--	--	--
Prototype No. 8	24	8	--	90	.27	.09	--
R&M Aircraft	--	--	--	324	--	--	--
Five Confirmatory Aircraft	238	65	166	731	.33	.09	.23
Nine Production Aircraft	79	--	--	344	.23	--	--
Average					.29	.06	.12

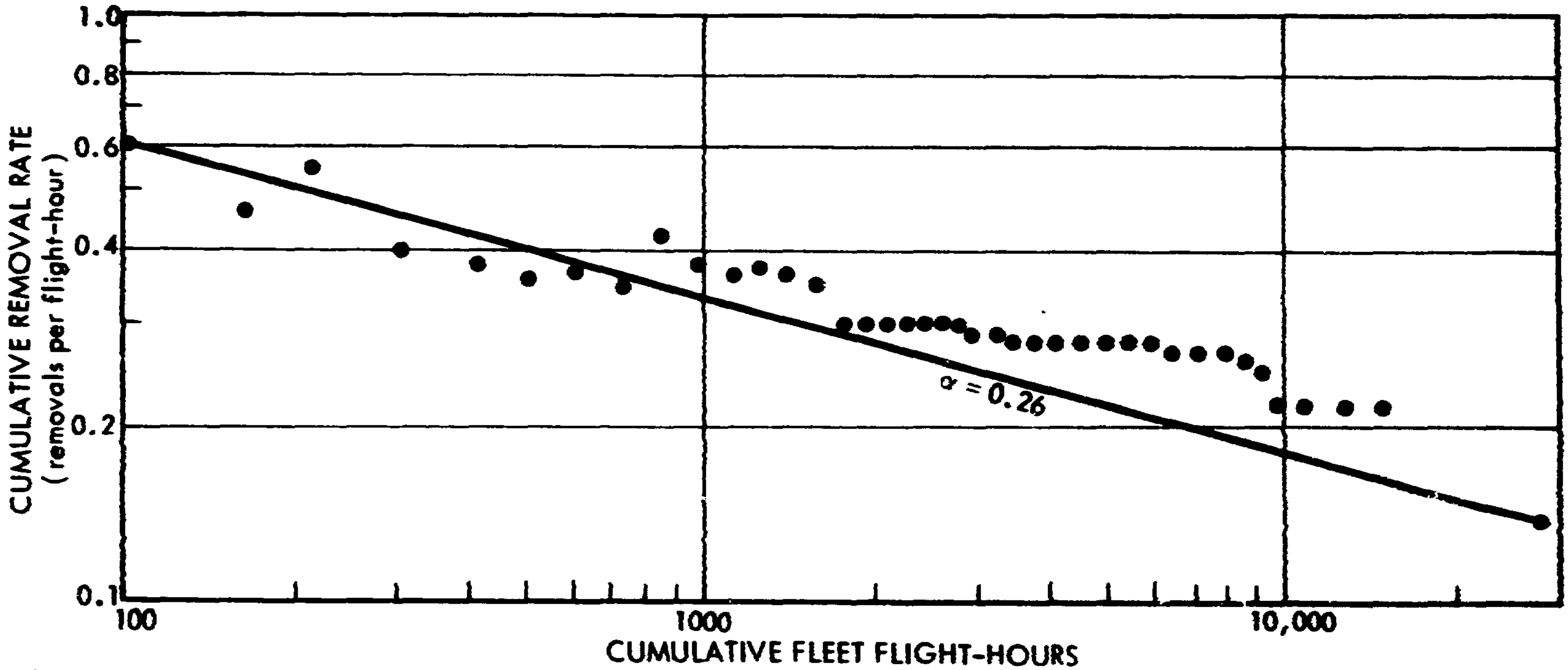


Figure 82. OH-6A CUMULATIVE REMOVAL RATE VERSUS CUMULATIVE FLIGHT-HOURS

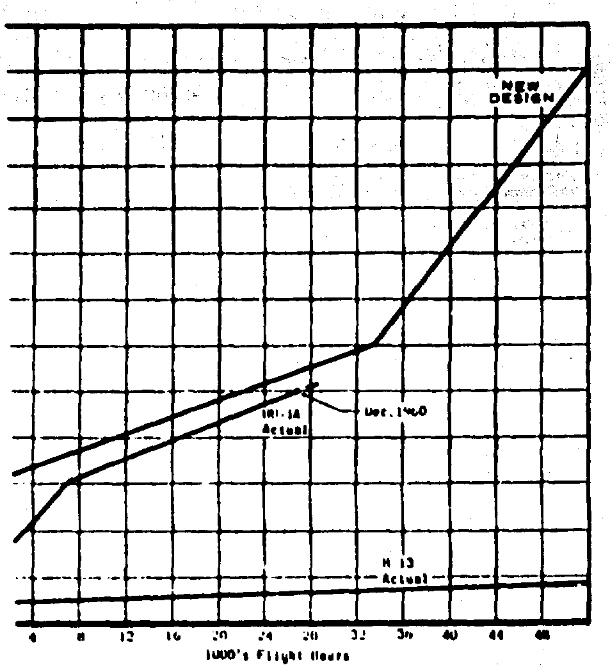
rate considerably from that of the earlier aircraft. However, if we accept the final point as valid and put a trend line from it to the initial point, we obtain a rate of growth corresponding in the Duane formulation to $\alpha = 0.26$, which is the maximum α that could be ascribed to these data. The removal rates of Figure 82 include all major components for the complete aircraft.

C. BELL

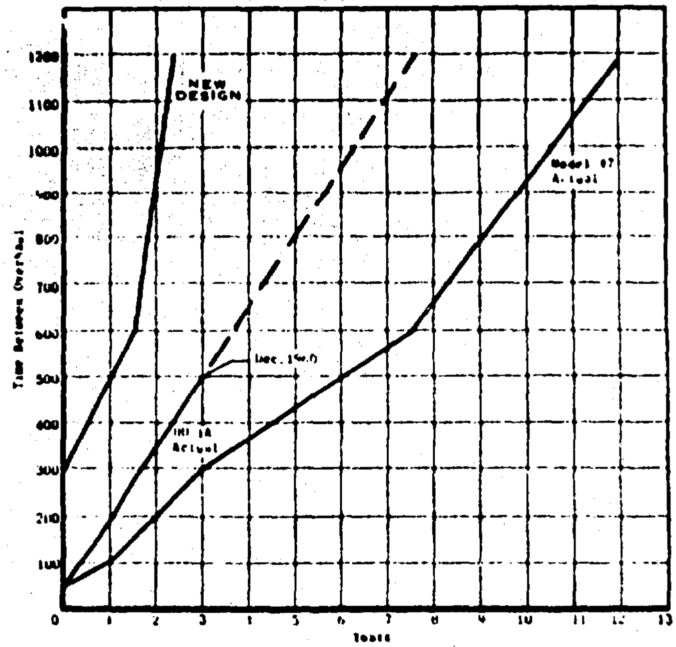
Bell Helicopter Company has been conducting a study of helicopter reliability growth for the Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Ft. Eustis, Virginia, under Contract DAAJ02-73-0097. A preliminary (and unapproved) report [27] has been prepared. The report analyzes the reliability growth characteristics of the development and early production of UH-1D, AH-1G, and OH-58A helicopters. The results indicate that, depending on the reliability-program effort planned for the design phase, the MTBF at 100 flight-hours was between 20 and 30 percent of the MTBF for the mature production aircraft. It sould be noted that these three helicopter programs were derivatives of earlier programs and that these results may not be representative of a completely new helicopter program.

It must be stressed that these findings are preliminary and may be changed as a result of further analysis. The final approved version of the Bell report is expected to be available in the third quarter of 1975. Ft. Eustis technical direction is being provided by Mr. V. W. Wellner (the Contracting Officer's Technical Representative) and Mr. T. L. House (of the Military Operations Technology Division).

Time Between Overhaul (TBO). Figure 83 (taken directly from a Bell Helicopter paper [28]) shows the progression in TBOs for the H-13 and HU-1A helicopter programs. Both show



FLIGHT TIME TO INCREASE TBO



CALENDAR TIME TO INCREASE TBO

ɪurce: Reference [28].

igure 83. HU-1A AND H-13 (MODEL 47) FLIGHT AND CALENDAR TIMES TO INCREASE TBO

ɔwth in this reliability measure, with the more recent (HU-1A) ɔgram showing a faster rate of TBO growth in terms of both ight time and calendar time. Since overhaul of major comıents is relatively costly, growth in TBO is important in ducing total maintenance costs. Of course, not every unit ɪches its nominal TBO; hence, a more important reliability ɪsure is the actual MTBO.

SIKORSKY

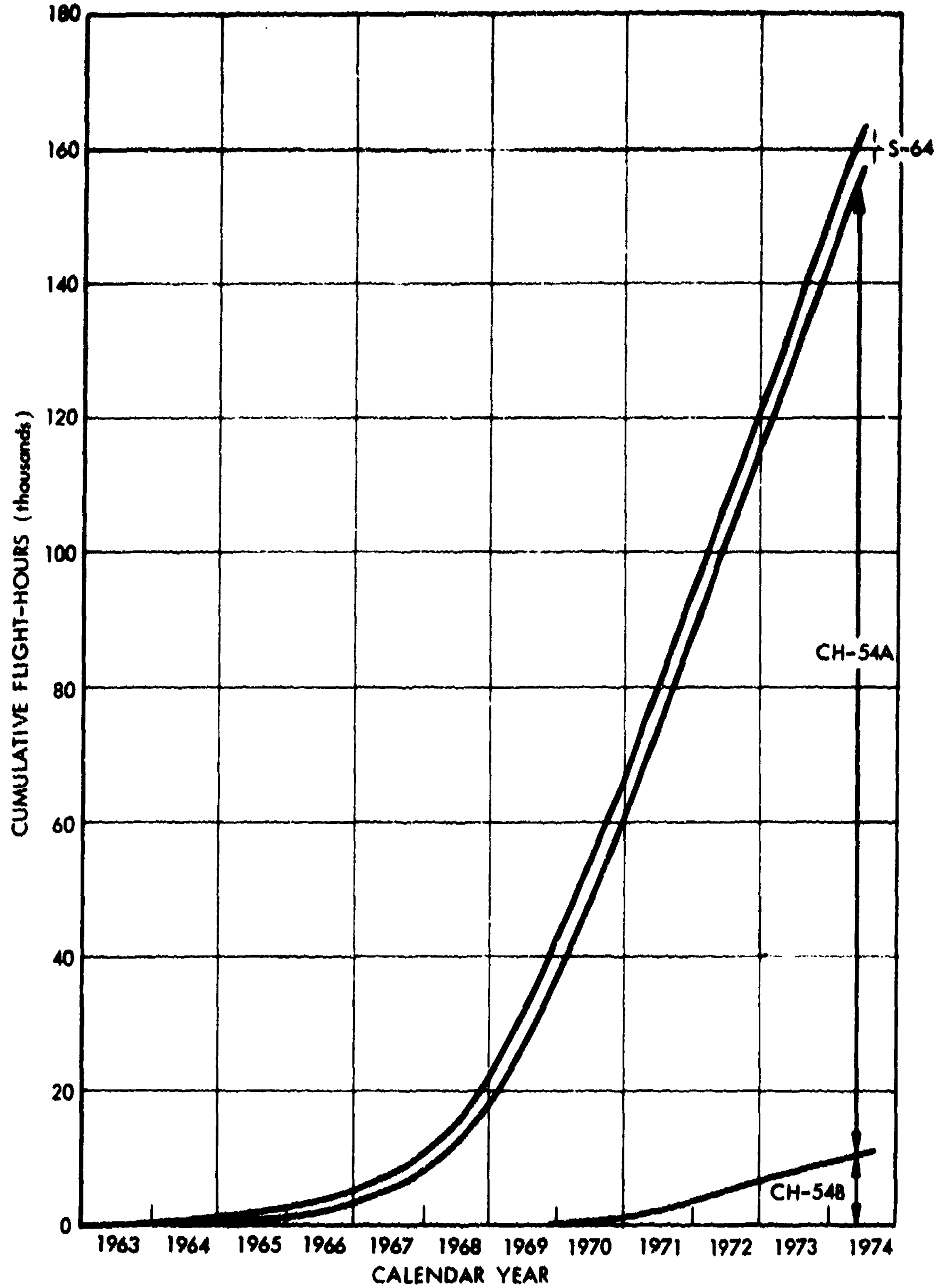
Part C of Volume 2 presents R&M data (obtained under subtract from Sikorsky Aircraft) for the H-53 and H-54 series helicopters. Sikorsky was not able to locate a significant ınt of time-series R&M data for any of their earlier pro- ıs. The H-53 and H-54 data consisted mainly of quarterly

R&M reports prepared under Navy and Army contracts. Because of the bulk of these reports (References [29] - [34]), only the most interesting sections of the final quarterly reports of the CH-53 Readiness Program series and the CH-54A Operations Reliability/Engineering Program series are presented in Volume 2. R&M data from these reports have been extracted (and are discussed below) for the two basic types.

1. S-64/CH-54A/CH-54B

The commercial S-64 was developed as a company project by Sikorsky and started flying in mid-1962. A military derivative, the CH-54A, was then sold to the Army and started flying about April 1964.

In November 1968, Sikorsky announced that it had received an Army contract to increase the payload capacity of the CH-54 from 10 to 12.5 tons. The 12.5-ton-payload version was designated the CH-54B. The contract called for a number of design improvements to the engine, gearbox, rotor head, and structure; altitude performance and hot-weather operational capability were also to be improved. The original JFTD12-4A engines were replaced by two Pratt & Whitney JFTD12-5As, each rated at 4,800 hp, and a gearbox capable of receiving 7,900 hp from the two engines was introduced. Single-engine performance was increased, since the new gearbox receives 4,800 hp from one engine, compared with 4,050 hp on the CH-54A. A new rotor system was also introduced, utilizing a high-lift rotor blade with a chord some 2.5 inches greater than that of the blade used formerly. Other changes included the provision of dual wheels on the main landing gear, an improved automatic flight-control system, and some general structural strengthening throughout the aircraft. Gross weight was increased from 42,000 to 47,000 pounds [35]. The CH-54B started flying in 1969. Cumulative flight-hours for the S-64/CH-54A/CH-54B family of aircraft are shown in Figure 84.



2-27-75-9

Figure 84. S-64/CH-54A/CH-54B CUMULATIVE FLIGHT-HOURS

Sections I.A.2, I.A.5, I.A.6, and II.A.1 include CH-54 service-reported R&M data. In addition to these data, Tables 43 and 44 present data for a number of R&M measures extracted from the quarterly R&M reports for the CH-54A (Ref. [33]) and the CH-54B (Ref. [34]). The quarters covered by the reports are shown in the first column of both Table 43 and Table 44. All the R&M measures of Tables 43 and 44 are cumulative for the CH-54A and the CH-54B (they start anew for the CH-54B) and are discussed below.

a. Total Reliability

Total reliability is defined as the probability of no failure during a one-hour mission. This category applies to *all* classes of failure, regardless of degree of severity, and includes aborts, downs, minors, and malfunctions with no effect. The CH-54A total reliability worsened over time (from 0.848 to 0.785); for the CH-54B, it remained approximately constant but was somewhat worse than it was for the CH-54A.

b. Mission Reliability

Mission reliability is defined as the probability that an aircraft will experience no mission-aborting failure in a one-hour mission. For the CH-54A, the mission reliability improved slightly, while for the CH-54B it remained approximately constant and was about the same as it was for the CH-54A.

c. Active MMH/FH

Active MMH/FH for the CH-54A increased during its first year of operation and then remained approximately constant, at about 6.5 MMH/FH. This type of pattern is often found where new aircraft enter service and operate for an initial period with lower than the steady-state MMH/FH. The active MMH/FH for the CH-54B decreased from the first to the second quarter reported but then

Table 43. CH-54A AND CH-54B CUMULATIVE R/M MEASURES

Quarter	Total Reliability	Mission Reliability	Active MMH/FH	Operational Availability	MTBF (hours) All Failures	MTBF (hours) Mission Aborts	MTBR and TBO (hours) Main-Rotor Head MTBR	Main-Rotor Head TBO	APP Clutch MTBR	APP Clutch TBO	Tail-Rotor Blade MTBR	Tail-Rotor Blade TBO	Main-Rotor Damper MTBR	Main-Rotor Damper TBO	Main-Rotor Blade MTBR	Main-Rotor Blade TBO	Turbine Engine MTBR	Turbine Engine TBO	Inter-mediate Gear Box MTBR	Inter-mediate Gear Box TBO	Main-Gear Box MTBR	Main-Gear Box TBO	Tail-Rotor Head MTBR	Tail-Rotor Head TBO
CH-54A																								
1/68	--	--	6.0	--	3.06	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
2/68	.848	.987	4.6	49.0	6.05	52.3	330	375	311	500	620	--	*	--	2,970	5,000	--	600	816	1,200	360	500	720	800
3/68	.846	.983	5.2	53.7	6.00	56.7	323	375	282	500	583	--	.	--	3,640	5,000	384	600	882	1,200	387	500	683	800
4/68	.838	.985	5.7	54.3	5.64	66.4	335	375	312	500	606	--	67,298	--	3,900	5,000	442	600	976	1,200	565	750	696	800
1/69	.832	.985	6.4	49.8	5.45	64.6	345	375	310	500	785	--	47,677	--	4,910	5,000	479	600	1,040	1,200	610	750	787	800
2/69	.865	.988	6.6	48.8	6.90	85.5	342	375	300	500	855	--	30,519	--	4,110	5,000	620	800	1,070	1,200	663	800	700	800
3/69	.810	.986	7.0	48.8	4.75	71.2	309	400	223	500	363	--	398	400	1,369	5,000	531	800	949	1,200	632	800	539	800
4/69	.785	.985	6.7	50.5	4.12	68.2	313	400	249	500	381	--	397	400	1,375	5,000	503	800	931	1,200	554	800	512	800
1/70	.784	.986	6.2	52.0	4.10	69.3	305	400	276	500	328	--	386	400	1,230	5,000	498	800	922	1,200	524	800	533	800
2/70	.785	.987	6.4	54.1	4.12	76.6	322	400	309	500	374	--	391	400	1,457	5,000	476	800	900	1,200	492	800	545	800
3/70	.785	.988	6.4	54.3	4.12	80.1	291	400	311	500	345	--	395	400	1,017	5,000	466	800	873	1,200	448	800	559	800
CH-54B																								
2/71	.698	.986	12.8	46.9	2.78	70.2	*	500	70	500	--	--	318	400	--	--	467	1,000	-	1,200	273	1,000	-	800
3/71	.741	.985	6.9	38.6	3.32	65.8	*	500[b]	112	500[a]	--	--	*	400[b]	--	--	524	800	-	500[a]	228	250[c]	-	800
4/71	.721	.981	7.3	48.7	3.06	51.3	380	500[b]	88	500[a]	--	--	745	400[b]	--	--	535	800	-	500[a]	423	500[c]	-	800
1/72	.696	.979	8.4	51.3	2.76	47.5	439	500[b]	99	500[a]	--	--	756	400[b]	--	--	582	800	-	500[a]	450	500[c]	-	800
2/72	.730	.985	7.4	54.6	3.18	64.3	534	500[b]	153	500[a]	--	--	770	400[b]	--	--	614	800	-	500[a]	466	500[c]	-	800
3/72	.726	.984	7.7	53.3	3.12	62.9	493	500[b]	142	500[a]	--	--	755	400[b]	--	--	511	800	-	500[a]	426	500[c]	-	800
4/72	.718	.983	7.7	53.3	3.01	58.3	421	500[b]	171	500[a]	--	--	619	400[b]	--	--	550	800	5,478	500[a]	437	500[c]	-	800
1/73	.711	.983	7.8	48.4	2.93	58.4	444	500[b]	185	500[a]	--	--	580	400[b]	--	--	540	800	6,652	500[a]	439	500[c]	-	800
2/73	.704	.984	7.5	50.6	2.85	63.8	448	500[b]	176	500[a]	--	--	561	400[b]	--	--	512	800	7,405	500[a]	411	500[c]	-	800
3/73	.709	.985	7.4	51.1	2.90	68.2	451	500[b]	189	500[a]	--	--	561	400[b]	--	--	519	800	8,112	500[a]	418	500[c]	-	800
4/73	.705	.986	7.5	50.1	2.86	71.4	586	500[b]	189	500[a]	--	--	1,407	400[d]	--	--	508	800	1,119	500[e]	541	625[bc]	-	800
1/74	.702	.986	7.3	50.1	2.83	72.2	576	500[b]	176	500[a]	940	1,630	1,438	400[d]	1,888	2,500	514	800	1,125	500[e]	547	625[b]	-	800

[a]And on condition.
[b]And 800 hours.
[c]And 1,000 hours.
[d]And 7,200 hours.
[e]And 1,200 hours.

Table 44. CH-54A AND CH-54B MAJOR SYSTEMS CUMULATIVE TOTAL RELIABILITY (ALL FAILURES)

Quarter	MTBF (hours)															
	Total Aircraft	Airframe	Landing Gear	Mechanical Flight-Controls	Rotors and Blades	Power Plant	Trans-mission	Auxiliary Power Plant	Electrical	Hydraulics	Fuel	Furnish-ings	Navigation	Communica-tions	Automatic Flight-Control System	Instruments
C-54A																
1/68	3.06	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
2/68	6.05	188.7	310.0	255.3	33.9	30.6	45.7	114.2	98.6	47.2	620.0	149.7	2,170.1	81.9	868.0	166.9
3/68	6.00	247.7	161.5	464.3	29.2	28.9	53.1	114.3	140.2	55.4	437.0	140.2	1,061.4	71.4	412.8	176.9
4/68	5.64	167.4	153.6	361.8	32.4	28.2	45.8	105.8	136.8	56.9	415.4	130.4	400.6	69.2	311.6	111.0
1/69	5.45	172.7	135.8	338.1	33.6	26.9	43.9	91.9	137.0	62.6	418.2	126.1	397.3	67.9	233.7	88.3
2/69	6.90	216.4	186.6	383.9	40.4	34.7	53.7	118.3	173.9	80.4	549.9	171.0	508.6	88.5	317.9	108.2
3/69	4.75	127.2	116.3	254.3	28.0	23.7	35.2	95.0	134.9	64.8	294.2	113.6	339.1	58.8	226.1	76.1
4/69	4.12	98.5	81.3	177.1	26.4	21.7	31.4	85.2	113.5	54.7	217.1	94.1	270.4	57.5	202.4	54.8
1/70	4.10	89.4	82.7	167.7	27.7	22.0	30.6	84.1	110.4	54.1	210.1	92.3	279.0	59.8	200.5	52.2
2/70	4.12	75.7	80.4	139.7	29.5	21.8	31.0	87.7	108.4	56.3	195.5	93.0	275.9	63.4	206.6	52.5
3/70	4.12	71.2	80.9	133.7	29.8	21.8	30.9	89.2	107.9	57.4	197.5	93.4	282.3	65.5	206.9	53.2
C-54B																
2/71	2.78	70.2	46.8	280.6	35.1	12.8	16.5	56.1	40.1	46.8	280.6	--	140.3	56.1	140.3	31.2
3/71	3.32	54.8	101.2	219.3	45.4	14.5	25.8	73.1	62.7	42.4	54.8	--	657.8	62.7	59.8	47.0
4/71	3.06	52.8	84.0	205.2	43.0	15.5	25.7	52.8	54.3	39.3	73.9	--	369.4	66.0	42.0	33.0
1/72	2.76	41.0	54.0	264.1	41.7	14.1	24.8	51.7	55.3	39.6	72.0	--	264.1	56.6	41.0	29.4
2/72	3.18	47.6	61.1	333.3	46.4	15.7	29.1	65.5	70.5	50.2	96.5	--	174.6	67.9	48.9	31.1
3/72	3.12	46.2	57.3	282.9	46.2	15.2	29.0	64.7	55.9	48.7	116.1	--	174.1	68.6	45.3	34.6
4/72	3.01	45.3	51.7	260.9	40.0	15.4	27.5	57.7	52.2	48.5	130.4	--	166.0	66.0	43.8	32.6
1/73	2.93	46.5	50.4	166.3	31.8	16.3	25.9	56.4	48.9	50.8	130.4	--	170.6	65.9	44.4	31.5
2/73	2.85	42.1	43.3	157.6	29.3	16.4	25.1	59.7	45.2	52.2	142.4	--	161.0	64.4	46.0	31.0
3/73	2.90	45.3	44.1	150.2	28.5	17.0	26.3	62.9	44.1	52.3	124.8	--	159.1	62.4	47.7	33.3
4/73	2.86	47.5	43.4	157.3	28.0	16.7	26.2	64.4	41.2	53.1	128.7	--	151.7	59.4	46.2	32.1
1/74	2.83	48.8	43.7	117.5	27.1	16.5	26.1	63.3	41.5	56.6	131.0	--	150.4	58.1	45.6	31.3

remained approximately constant--at 7.4, a level moderately higher than it was for the CH-54A.

d. Operational Availability

Operational availability depends not only on the intrinsic R&M characteristics of the aircraft but also on the level of maintenance personnel, equipment, and spare parts available to maintain the aircraft. Hence, operational availability is an imperfect measure of R&M characteristics; nevertheless, differences in R&M characteristics are generally reflected in operational availability rates.

Operational availability of the CH-54A increased initially (from the second to the third quarter of 1968) and then remained approximately constant, at about 52 percent. For the CH-54B, it increased over the first year of operation and then remained approximately constant at about 51 percent--about the same rate as for the CH-54A.

e. MTBF (All Failures)

The next column of Table 43 shows MTBF for all failures for the complete aircraft. This column is repeated in Table 44, which also shows the breakdown of MTBF for most of the aircraft systems. For the total aircraft, the MTBF for the CH-54A improved (increased) from the first to the second quarter of 1968 and then worsened (decreased), from about 6.0 to 4.1 hours. For the CH-54B, it improved from the second to the third quarter of 1971 and then worsened, from about 3.3 to 2.8 hours--a rate considerably worse than that of the CH-54A. The MTBFs for the major systems shown in Table 44 generally follow the trend of the total aircraft; in most cases, there is a worsening trend starting with the second quarter reported for each aircraft. For the CH-54A, 13 of the 15 systems show a worsening MTBF trend, while the other two remain approximately constant.

For the CH-54B, six of the 14 systems show a worsening trend, five remain approximately constant, and three show an improvement in MTBF. At the end of the reporting period for each aircraft, 12 of the 14 systems showed a worse MTBF on the CH-54B than on the CH-54A; the other two systems had about the same MTBF on both aircraft. In general, the MTBFs for the total aircraft and for the individual systems worsened on both the CH-54A and the CH-54B, and the CH-54B was worse than the CH-54A.

f. MTBF (Mission Aborts)

The next column of Table 43 shows MTBF for those failures of such a nature that they result in a mission abort. For this class of failures, the CH-54A showed improvement (from about 54 to 80 hours) and the CH-54B improved slightly (from about 65 to 72 hours, a level slightly worse than for the CH-54A). The MTBFs for individual systems were not extracted as they were in Table 44 for *all* failures. They would probably show, in general, the same improvement trends as noted above for the total aircraft. The trends for all failures are probably more reliable than the trends for mission-aborting types of failures, because subjective judgment is involved in determining which failures are serious enough to result in a mission abort.

It is interesting to note that the MTBF for all failures worsened for both aircraft, while the MTBF for mission-abort-type failures improved for both aircraft--which would indicate that action was taken to correct the more serious type of failures (those causing mission aborts) but that the more minor types of failures were relatively ignored and increased in frequency as the fleets aged.

g. MTBR and TBO

The final section of Table 43 shows MTBR and TBO for a number of major components. These are the types of components

that are removed from the aircraft and overhauled either when they fail or at a specified time (TBO).

Main Rotor Head. The MTBR for the CH-54A main-rotor head worsened slightly, from about 330 to 291 hours. At the same time, the TBO was increased from 375 to 400 hours. Table 43 shows an infinite MTBR for the CH-54B main-rotor head during the first two quarters--which simply indicates that no removals occurred during those two quarters. Starting with the third quarter reported, the MTBR for the CH-54B improved from about 400 to 580 hours, considerably better than the experience of the CH-54A. The TBO was increased to 500 and 800 hours for two different models of the main-rotor head, both being operated simultaneously.[1]

Auxiliary Power Plant (APP) Clutch. The MTBR for the CH-54A APP clutch remained approximately constant, at about 311 hours; its TBO was constant, at 500 hours. The MTBR for the CH-54B improved from about 100 to 180 hours, but was considerably worse than that of the CH-54A. In simultaneous service use on the CH-54B were two models, one of which had a TBO of 500 hours and the other of which had no TBO (replaced "On Condition").

Tail-Rotor Blade. The MTBR for the CH-54A tail-rotor blade worsened, from about 600 to about 350 hours; no TBO was shown for this item. For the CH-54B, the MTBR was reported only for the final quarter. The MTBR of 940 hours was almost three times better than that for the CH-54A. The corresponding TBO was 1,600 hours.

---

[1] In a number of cases, a component is shown with two or more TBOs at the [illegible]; these TBOs are associated with different models of the component [illegible] period of [illegible].

Main-Rotor Damper. The MTBRs for the CH-54A main-rotor damper from the fourth quarter of 1968 to the second quarter of 1969 are probably wrong, since the MTBRs are greater than the total fleet flight-hours (see Figure 84, above). In the third quarter of 1969, the total MTBR dropped to 398 hours and then remained approximately constant (at about 395 hours) for the next five quarters. During this period, its TBO was 400 hours. The MTBR figures for the CH-54B also look questionable; they jumped from 561 hours in the third quarter of 1973 to 1,407 hours in the fourth quarter of 1973. However, its level of MTBR appears improved over that of the CH-54A--at least for the latter's last five quarters. The TBOs for the CH-54B were 400 and 800 hours through the third quarter of 1973 and 400 and 7,200 hours for the last two quarters reported.

Main-Rotor Blade. The MTBR for the CH-54A appears questionable; it dropped from 4,110 in the second quarter of 1969 to 1,369 in the third quarter of 1969. After that large questionable drop, its MTBR worsened, from about 1,370 to 1,017 hours. Its TBO throughout was 5,000 hours. The MTBR for the CH-54B was reported only for the final quarter; at 1,888 hours, it was considerably improved over the final MTBR of the CH-54A, while its TBO had been reduced to 2,500 hours--one half that for the CH-54A.

Turbine Engine. The MTBR for the CH-54A remained approximately constant (at about 470 hours), while its TBO increased from 600 to 800 hours. For the CH-54B, the MTBR worsened slightly (from about 540 to 510 hours), but was slightly better than that of the CH-54A. Its TBO increased to 1,000 hours in the first quarter reported but then dropped to 800 hours and remained there throughout the reporting period.

Intermediate Gear Box. The MTBR for the CH-54A remained approximately constant at about 900 hours; the TBO also remained constant at 1,200 hours. The MTBR for the CH-54B looks questionable because of the sharp drop between the third and the fourth quarter of 1973. However, the relatively low numbers reported in the last two quarters still showed improvement over that of the CH-54A. For the first ten quarters, the TBOs were 500 hours; for the last two quarters, they were 500 and 1,200 hours.

Main Gear Box. The MTBR for the main gear box of the CH-54A worsened slightly (from about 550 to about 450 hours). However, over this same period of time, the TBO was increased in two steps (from 500 to 800 hours). The MTBR for the CH-54B improved from 400 to 547 hours, a level slightly better than that of the CH-54A. Several models of the main gear box were in service, with TBOs varying from 250 to 800 hours.

Tail-Rotor Head. The MTBR for the CH-54A worsened (from about 700 to 550 hours); its TBO remained constant (at 800 hours). No removals were recorded for the CH-54B, even though the TBO remained at 800 hours. The MTBR reporting for the CH-54B is probably in error.

The MTBR and TBO trends are summarized in Table 45. As can be seen by the totals (for the three types of trends) at the bottom of the table, the results are mixed. For the CH-54A, the MTBR trends were generally worsening; all nine components either worsened or remained constant. On the other hand, the MTBR trends for the CH-54B generally improved; three improved, while only one worsened. Further, at the end of the reporting period for each aircraft, the CH-54B components were improved relative to those of the CH-54A in seven of the eight cases for which data were available for comparison. Any overall evaluation [illegible] of MTBR [illegible] data is difficult to make; with

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Table 45. MTBR AND TBO TRENDS FOR CH-54A AND CH-54B COMPONENTS

Component	CH-54A		CH-54B		CH-54B Relative to CH-54A	
	MTBR	TBO	MTBR	TBO	MTBR	TBO
Main-Rotor Head	W	I	I	I	I	I
APP Clutch	C	C	I	C	W	I
Tail-Rotor Blade	W	-	-	-	I	-
Main-Rotor Damper	C	W	-	I	I	I
Main-Rotor Blade	W	C	-	-	I	W
Turbine Engine	C	I	W	W	I	C
Intermediate Gear Box	C	C	-	W	I	W
Main Gear Box	W	I	I	-	I	-
Tail-Rotor Head	W	-	-	-	-	-
Totals W:	5	1	1	2	1	2
C:	4	3	0	1	0	1
I:	0	3	3	2	7	3

Key: W = worsening trend;
C = constant; and
I = improving trend.

that caveat, we will conclude that MTBRs tend to worsen for the first few years of service (the CH-54A period) and then improve with the introduction of a later model of the aircraft (the CH-54B period).

TBOs in general tend to increase, but not as uniformly as one might expect. In the case of the CH-54A, three increased while one was reduced; for the CH-54B, the same number (two) increased as were reduced.

The correlation between MTBRs and TBOs is much weaker than one might expect. In the case of the CH-54A, all the MTBRs worsened or remained constant, while six of the seven TBOs increased or remained constant. On the other hand, the MTBRs of the CH-54B improved relatively more than the TBOs. The lesson

to be learned from this analysis is that increasing TBOs should not be assumed automatically to reflect improved MTBRs.

h. Summary of R&M Trends

The trends of the eight R&M measures (presented above) for the CH-54A and CH-54B are summarized in Table 46, which indicates that there were about the same number of worsening trends (8 total) as there were improving trends (7 total). Hence, without any weighting of relative importance, the data indicate an overall approximately constant level of R&M measures for the CH-54A/B family of aircraft.

A crude weighting of the R&M measures of Table 45 can be accomplished by eliminating the less important measures and the measures that are redundant. Based on these criteria, the following four measures could be eliminated: (1) operational availability, because it depends on many factors other than intrinsic R&M characteristics; (2) MTBF (All Failures) and (3) MTBF (Mission Aborts), because they are reflected in total and mission reliability; and (4) TBO, because overhaul costs are driven by MTBR, not TBO. If these four R&M measures are dropped, the results are essentially the same as before: there were still about the same number of worsening trends (4 total) as there were improving trends (3 total)--again indicating an overall approximately constant level of R&M measures for the CH-54A/B family of aircraft.

Table 46. SUMMARY OF CH-54A AND CH-54B R&M TRENDS

R&M Measure		CH-54A	CH-54B	CH-54B Relative to CH-54A
Total Reliability		W	C	W
Mission Reliability		I	C	C
Active MMH/FH		C	C	W
Operational Availability		C	C	C
MTBF (All Failures)		W	W	W
MTBF (Mission Aborts)		I	I	W
MTBR		W	I	I
TBO		I	C	I
Totals	W:	3	1	4
	C:	2	5	2
	I:	3	2	2

Key: W = worsening trend;
C = constant; and
I = improving trend.

2. CH-53/RH-53/HH-53

The CH-53A, the first of the H-53 series, was developed for the Marine Corps and flew first in October 1964; deliveries began in mid-1966. In September 1966, the Air Force ordered eight HH-53Bs; the first flight was in March 1967, and deliveries began in June 1967. The HH-53C, an improved version of the HH-53B, was first delivered to the Air Force in August 1968. A total of 66 HH-53B/Cs were built. The CH-53D, an improved version of the CH-53A for the Marine Corps, was first delivered in March 1969. The last CH-53D (the 265th CH-53 built) was delivered in January 1972. In early 1971, the Navy borrowed 15 CH-53As to form the first helicopter mine countermeasures (MCM) squadron. The RH-53D(MCM) was flown first in October 1972, and deliveries began in September 1973. In addition to these U.S. military versions of the H-53, a total of 153 CH-53Gs are being

produced for the German armed forces; the first delivery of this version was in March 1969. There have also been eight CH-53s delivered to Israel and two to Austria [25]. Cumulative flight-hours for the H-53 family of aircraft are shown in Figure 85.

Sections I.B.5, I.C, and II.A.2 include H-53 service-reported R&M data. In addition to these data, we obtained data from Sikorsky on abort rates and MTBRs for major components.

a. Abort Rates

Figure 86, taken directly from a Sikorsky report, shows the CH-53A/D abort rate (in aborts per hour) versus accumulated flight-hours. Figure 87, from another Sikorsky report, shows in greater detail the abort-failure trend for the first 600 flight-hours. Figure 88 shows in more detail the data points for the last segment of Figure 86 (covering the period October 1969 to June 1971); in addition, it shows from mid-1971 to mid-1973 the abort rate for the 15 CH-53As operated by the Navy as MCM helicopters.

Figure 86 indicates an abort rate per hour of about 0.28 at 100 flight-hours, while Figure 87 indicates a rate of about 0.22 at 100 hours (the slope of the curve at 100 hours). In either case, there was a marked decrease in abort rate from 0.22-0.28 at 100 hours to about 0.07 when the aircraft was introduced into field service (after about 5,000 flight-hours). The field rate dropped to about 0.03 after 40,000 flight-hours, but then rose to about 0.04 at 100,000 to 150,000 flight-hours. Figure 88 indicates that the abort rate remained at about 0.04 through the end of 1972, but then worsened markedly during the first half of 1973, to about 0.07 (but this is only for 15 RH-53s). This higher abort rate could have resulted from a more severe operating environment (MCM) than that of the Marine Corps' heavy-transport mission. Ignoring the last two data points of Figure 88, the field-abort rate showed a moderate

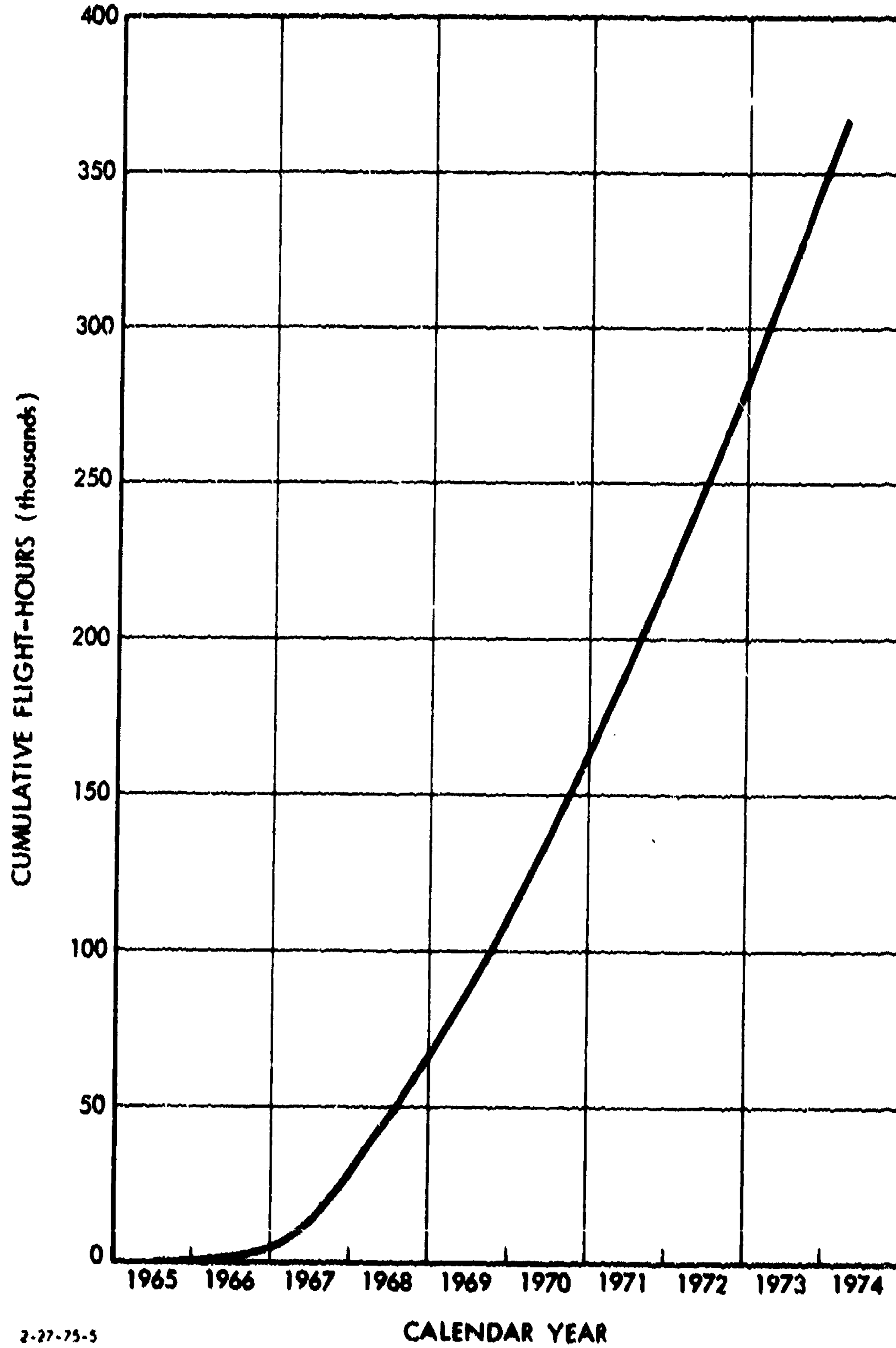


Figure 85. CH-53/RH-53/HH-53 CUMULATIVE FLIGHT-HOURS

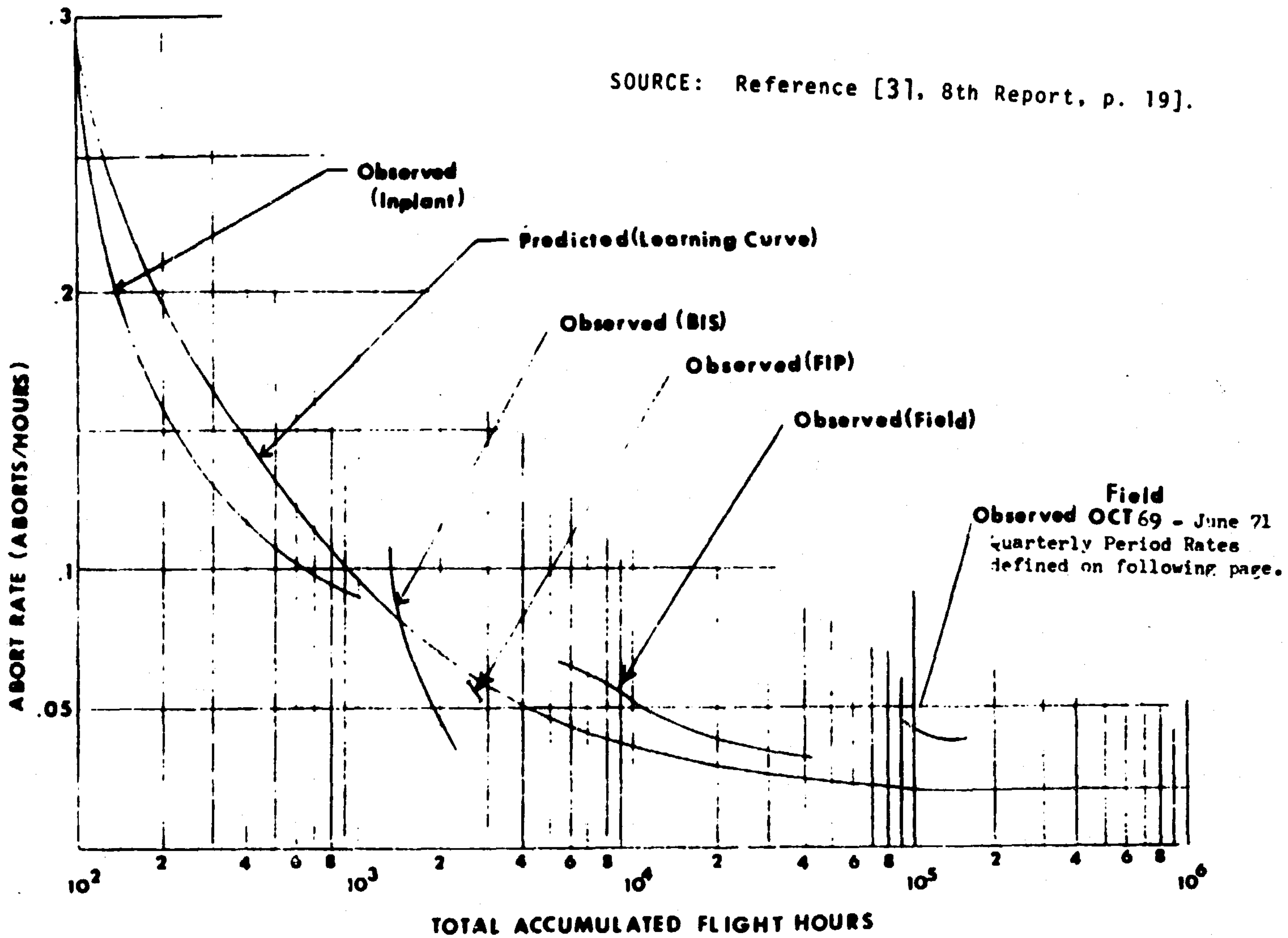
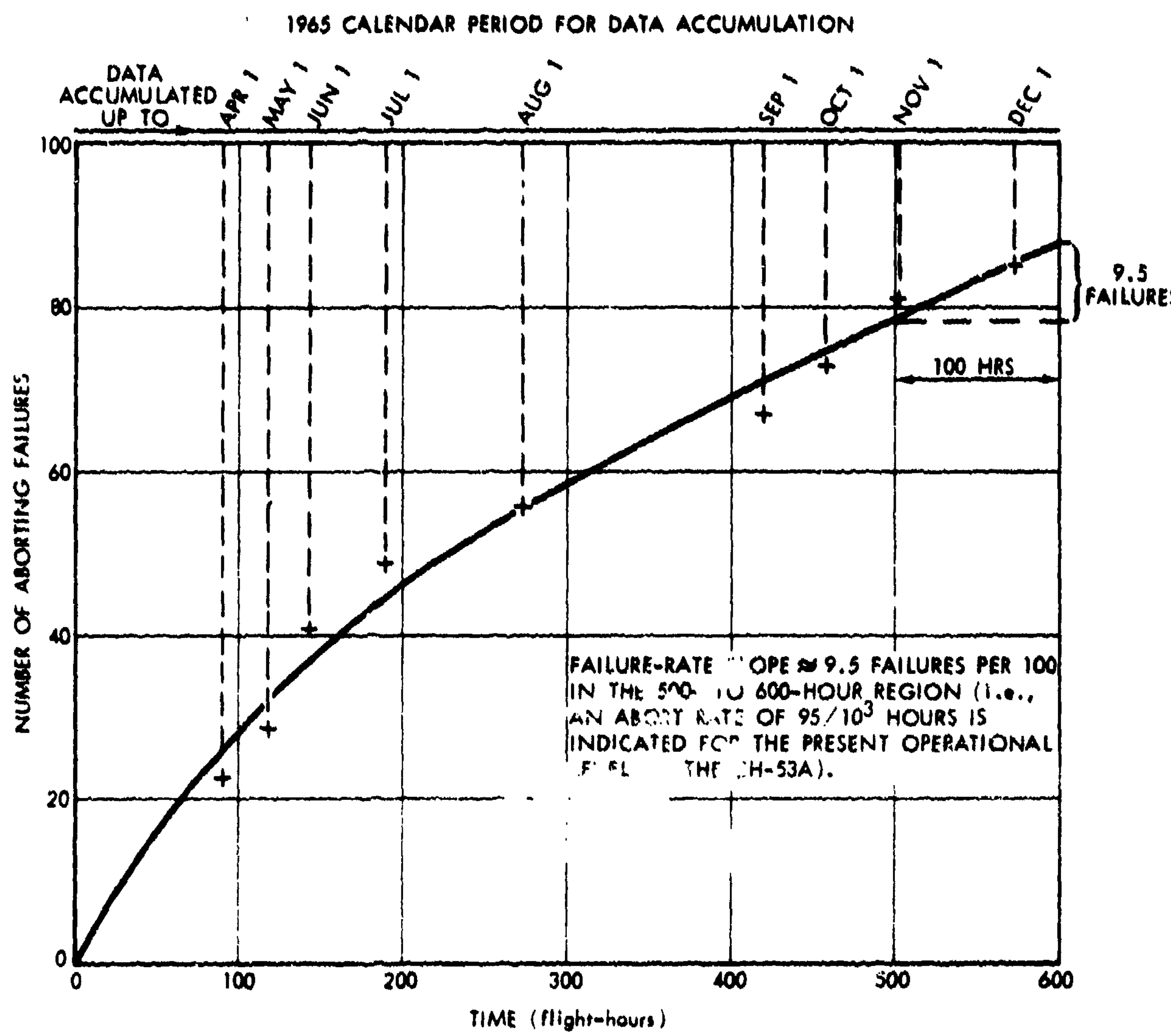
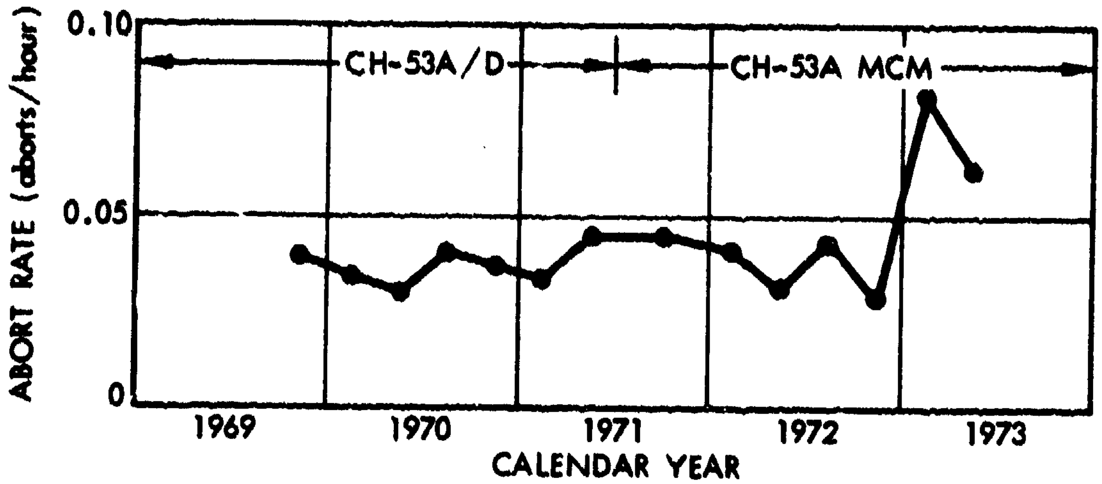


Figure 86. CH-53A/D ABORT RATE (EXPERIENCE VERSUS PREDICTED)



SOURCE: Reference [29, 4th Report].

Figure 87. MISSION-ABORT FAILURE TREND



SOURCES: To mid-1971 - Reference [31, 8th Report].
After mid-1971 - Reference [32, 1st Report].

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Figure 88. CH-53A/D AND CH-53A(MCM) ABORT RATES

improvement (from 0.07 to 0.04) following introduction into service.

It is interesting to note that there was an increase in abort rate every time the helicopter entered a new operating environment; these increases were probably due to the initial learning period of the new operating personnel. In Figure 86, a "Predicted (Learning Curve)" has been drawn by Sikorsky through the various curve segments for the different operating phases. Note that the "Predicted (Learning Curve)" is lower than the actual rates achieved in field service.

In Figure 89, these curves have been replotted on log-log paper; also shown on this paper are the slopes representing different Duane α's. As can be seen, depending on which parts of the curves are used, a wide range of α's can be obtained. From the initial point of the "Observed (In plant)" segment to any point on the first "Observed (Field)" segment, the α's lie in the range of 0.3-0.4.

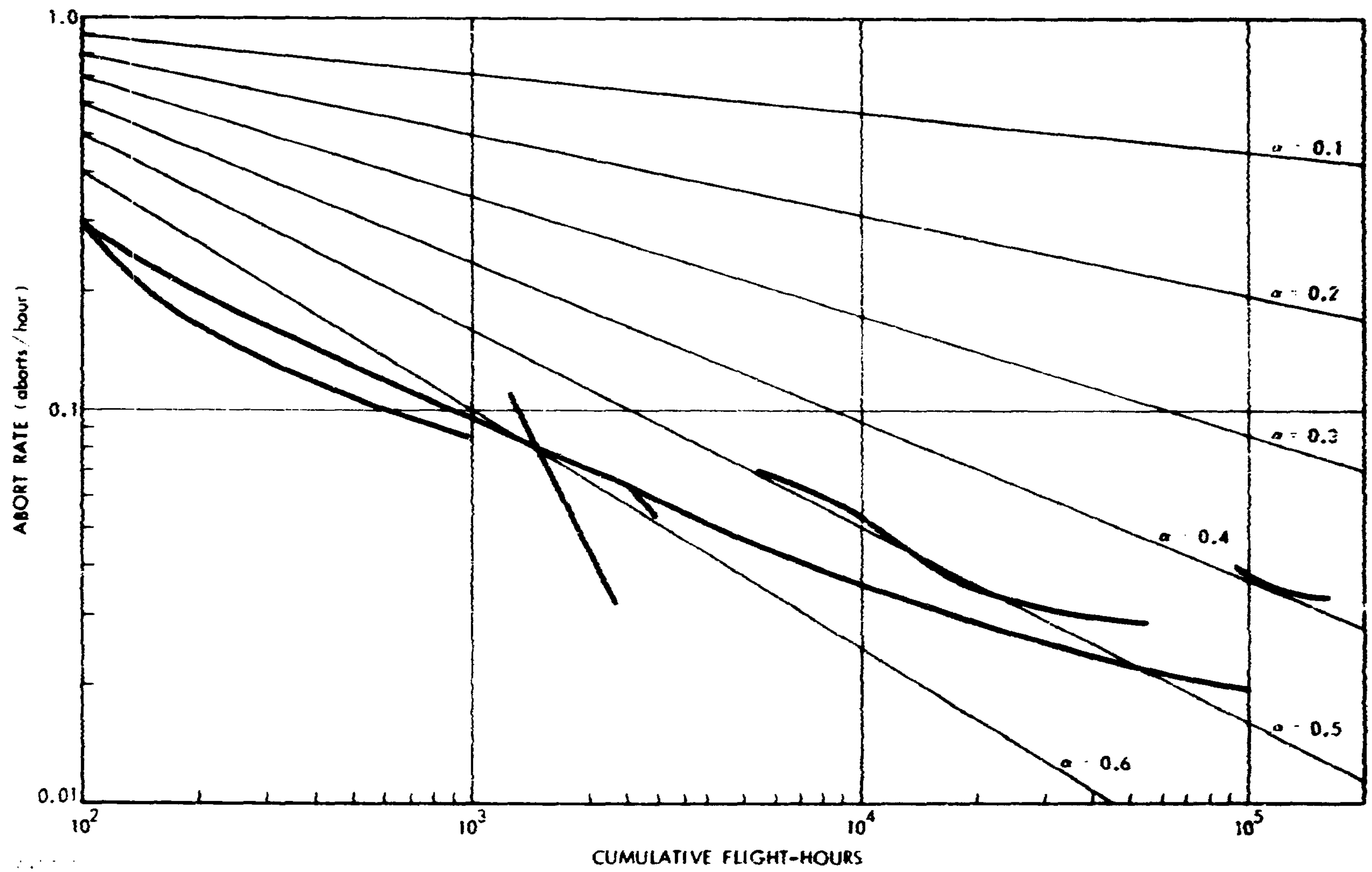

Figure 89. CH-53A/D ABORT RATE VERSUS CUMULATIVE FLIGHT-HOURS

Figure 90 shows mission reliability for the CH-53A, CH-53D, and HH-53B/C, where mission reliability is defined as the probability that an aircraft will experience no mission-aborting failure in a 1.5-hour mission. Note that Figure 90 is based on a 1.5 hour mission, while Figures 86-88 are abort rates (aborts per flight-hour). The mission reliability can be computed from the abort rate by means of the formula $e^{-\lambda t}$, where λ is the abort rate and t is the length of the mission in hours.[1] The time period of Figure 90 (fourth quarter of 1967 to third quarter of 1969) covers Figure 86's span of accumulated flight-hours from about 25,000 to 85,000 flight-hours. Figure 86 indicates an approximately constant abort rate of about 0.04 over this period, while Figure 90 indicates an improving mission reliability. This difference is due to the fact that Figure 86 is based on "observed" (unadjusted) aborts while Figure 90 is based on adjusted aborts. The adjustment involves the elimination of aborts judged to be due to causes other than the mechanical performance of the helicopter itself (see Volume 2, page 8-92, final paragraph). Page 8-99 of Volume 2 shows both observed and adjusted abort rates for the same basic data. The best *observed* abort rate for the H-53 is about 0.04, while its corresponding *adjusted* abort rate is about 0.025. However, even Figure 86 indicates an improvement from early field service (at about 5,000 flight-hours). Hence, we can conclude that the CH-53 *observed* abort rate dropped from about 0.07 during early service use to a stabilized level of about 0.04 after roughly 50,000 cumulative flight-hours.

b. MTBRs of Major Components

Table 47 presents cumulative MTBRs of major components for all CH-53A and CH-53D aircraft (including the 15 CH-53As loaned

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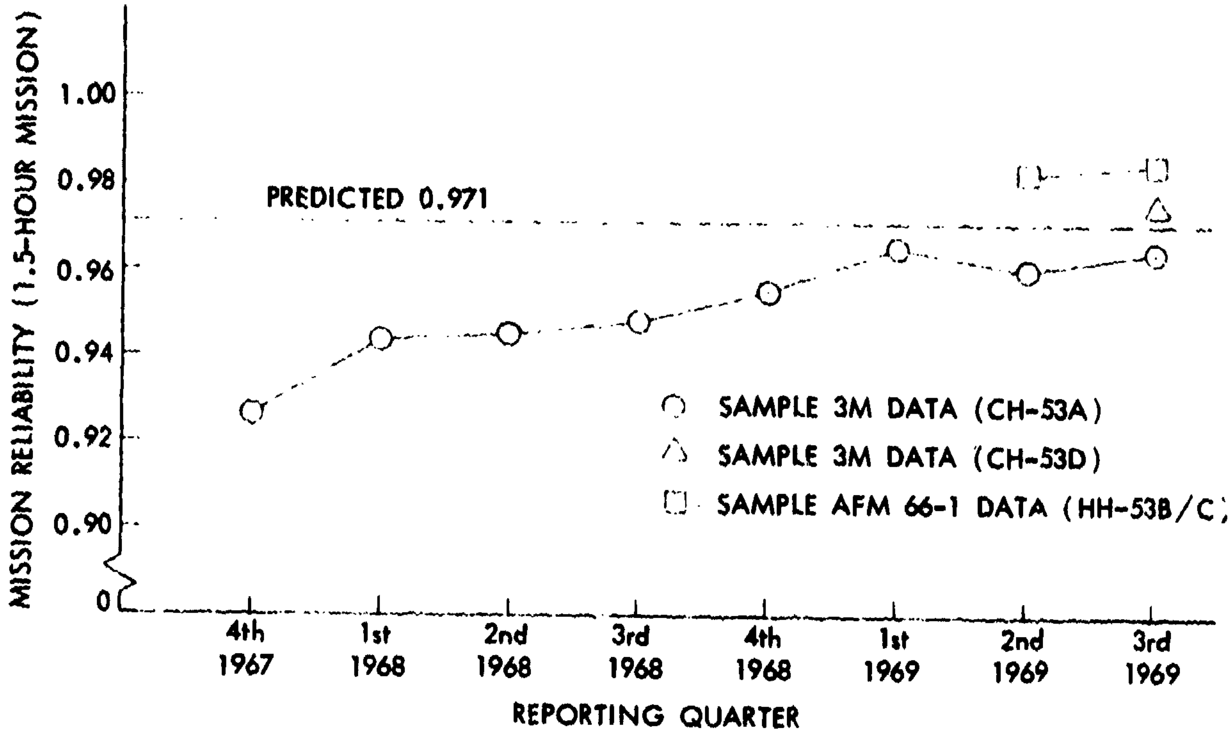
[1]The last three quarters of Figure 90 indicate a mission reliability of about 0.963 for the 1.5-hour mission; the corresponding abort rate (per hour) would be 0.025.



SOURCE: Reference [30, 2nd Report, p. 7].

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Figure 90. CH-53 AND HH-53 AIRCRAFT MISSION RELIABILITY

to the Navy for MCM use). The table covers the period from the end of 1967 (when cumulative flight-hours were about 29,000) through the periods noted (June 1970 to December 1973). There is a general trend of improvement in MTBR for these major components: 13 of the 14 showed improvement in MTBR; only the "Sleeve and Spindle" exhibited a worsening MTBR. In the last column of Table 47, the α's for the Duane formulation [26] are presented. The average value of α for all 14 components was 0.23.

Table 47. CH-53A/D MAJOR COMPONENT MTBR (HOURS)

[Statistical data accrued from 1967 through the periods noted]

Component	6/70	3/71	6/71	9/71	12/71	6/72	9/72	12/72	3/73	6/73	9/73	12/73	α
Main Gear Box	416	502	491	492	499	495	497	492	501	520	525	528	.27
Intermediate Gear Box	728	[illegible]	733	730	753	772	880	874	855	857	863	885	.33
Tail Gear Box	500	602	578	607	620	649	659	653	654	666	695	693	.40
Accessory Gear Box	518	551	559	579	574	570	575	602	600	606	600	623	.26
Nose Gear Box	490[a]	529	540	536	537	541	548	549	514	516	525	539	.09
Main-Rotor Head	329[b]	382	384	383	383	387	388	391	393	394	386	397	.19
Swashplate	416[b]	499	473	476	477	498	493	508	506	506	506	502	.18
Main-Rotor Damper	243	285	281	295	295	294	297	312	312	311	307	307	.24
Sleeve and Spindle	391	403	360	286	316	328	329	340	343	346	340	340	-.11
Tail-Rotor Head	465	509	485	483	464	489	493	491	499	500	507	517	.16
Tail-Rotor Servo	550	540	531	584	--	--	--	--	--	--	--	--	.27
Primary Servo	325	377	400	418	--	--	--	--	--	--	--	--	.30
Main-Rotor Blades	418	453	443	491	483	--	--	--	--	--	--	--	.42
Tail-Rotor Blades	372	327	375	383	384	--	--	--	--	--	--	--	.22

[a]Same figure through December 1969.

[b]Same figure through September 1969.

Sources: July 1970 - December 1971: Reference [31, 8th Report];
June 1972 - March 1973: Reference [32, 4th Report];
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APPENDIX A

CONTRACTUAL REQUIREMENTS FOR MEASURING MISSION AND SYSTEM RELIABILITY FOR THE AH-56A (CHEYENNE)

7.4.4 Mission Reliability Measurement

7.4.4.1 Mission Reliability Measurement Test Schedule - Measurement of mission reliability shall be accomplished utilizing all data derived from contractor and Government flight test programs. A measure of achieved reliability will be available with status reports provided as specified in the contract. All component time and failure data will be utilized to provide the broadest possible statistical base for conclusions.

7.4.4.2 Mission Success and Failure Criteria - For purposes of measuring AAFSS [Advanced Aerial Fire Support System, the AH-56A] reliability, mission reliability is defined as the probability that the AAFSS will successfully complete a mission of designated type and profile under specified flight conditions without any fault in any subsystem/component required for the mission, given that the AAFSS is operationally ready at the time of mission assignment. Failures and malfunctions of minor or non-essential components which do not affect mission capability are not considered mission failures. Mission failures criteria applicable to measurement of AAFSS reliability are presented, but not limited to those in Table D.

TABLE D

MISSION FAILURE CRITERIA

SYSTEM/SUBSYSTEM	FAILURE CONDITIONS
A Aerial Vehicle	
Airframe	Windshield failure to the extent that both pilot and copilot vision are obscured.
	Inadvertent loss of canopy.
	Loss of an external store required for mission.
	Any structural failure to the basic airframe that requires precautionary landing.
	Loss of an engine cowling, fairing, major access door, or cover.
Landing Gear	Failure of MLG to retract.
	Failure to sustain MLG in the up position.
	Failure to extend and lock MLG in the down position.

7.4.4.2 (Continued)

SYSTEM/SUBSYSTEM	FAILURE CONDITIONS
Power Plant and Related Systems	Less than 90 percent of installed power available.
	Engine caused forced shutdown.
	Loss of engine control.
	Failure to start.
Power Transmission	Loss of engine drive input power or failure of engine drive input section to provide to main rotor drive or tail rotor drive sections.
	Loss of tail rotor power, or failure of tail rotor drive to provide normal driving power.
	Individual loss of either main rotor drive power or accessory drive power.
	Loss of ability to provide required lubrication in the engine or power train lubrication systems.
Rotors, Props, and Accessories	Loss of any one rotor blade or portion thereof.
	Loss of pitch control function of forward propulsion propeller.
Hydraulics	Loss of hydraulic power to both Flight Control Hydraulic subsystems.
Instruments	Loss of BDHI or HSI.
	Complete loss of attitude indications.
	Complete loss of airspeed indication.
	Loss of both TIT indicators.
	Loss of any two engine tach indicators.
	Loss of both rotor tach indicators.
Electrical	Loss of more than 50 percent of AC power.
	Loss of two out of three TR units in the DC power subsystem.
Fuel	Loss of ability to provide required fuel to engine.

7.4.4.2 (Continued)

SYSTEM/SUBSYSTEM	FAILURE CONDITIONS
Flight Controls	Inability of gyro to control main rotor blade pitch.
	Inability to maintain functional control of the collective actuator.
	Loss of cyclic control.
	Inability to maintain control of the yaw actuator.
	Inability of the yaw actuator to control tail rotor blade pitch.
Utility	Loss of main rotor or anti-torque rotor, de-icing.
	False fire warning.
	Loss of engine inlet duct anti-icing/de-icing function.
	Complete loss of lighting to primary flight instruments.
Auxiliary Power Unit	Failure to start.
B Avionics	
Communications	Loss of both VHF/FM tactical RT functions.
	Loss of both ICS control subsystems.
	Loss of both Doppler Navigation and air mass sensing subsystems.
	Loss of both heading and attitude reference (HARS).
Computer Central	Loss of a single output function.
C Fire Control	
Pilot Sight	Loss of pilot sight subsystem.
Swiveling Gunner Station	Loss of gunner sight subsystem.
	Loss of azimuth tracking and inability to return to boresight stow position.
	Loss of missile guidance function.
Controls & Displays	Loss of missile control capability.

7.4.4.2 (Continued)

SYSTEM/SUBSYSTEM	FAILURE CONDITIONS
D Armament	
XM-140 Gun	Any inability to fire upon command.
XM-52 Subsystem	Any inability to fire on command.
XM-134 Gun	Any inability to fire on command.
XM-53 Subsystem	Any inability to fire on command.
XM-129 Grenade Launcher	Any inability to fire on command.
XM-51 Subsystem	Any inability to fire on command.
TOW Missile Subsystem	Any inability to fire on command.

7.4.4.3 Chargeable Failures - Failures will be included in the computation of mission reliability when one or more of the following conditions exist:

a. Multiple independent (primary) failure conditions detected on the vehicle during measurement time will be individually chargeable.

b. Involuntary stoppage caused by an independent (primary) failure condition; or forced stoppage judged necessary by the pilot or crew to prevent or eliminate airframe or engine damage and/or personnel hazard.

c. Failure condition as a result of fluid, fuel, or lubrication contamination where subsequent testing proves that the contamination levels are within the limits specified for use in the vehicle.

d. Undiagnosed failure conditions where failure symptom was detected and verified in subsequent retesting at the bench test level but diagnosis and determination of the basic cause could not be established.

e. Failure is induced in GFM by installation characteristics. Failure induced by such characteristic shall be chargeable to CFM reliability.

7.4.4.4 Non-Chargeable Failures - Failures will be excluded from the mission reliability computation when one or more of the following conditions exist:

7.4.4.4 (Continued)

a. The failure symptom detected at the vehicle cannot be duplicated during subsequent retest.

b. The failure symptom is detected on the vehicle when time is not being recorded by the appropriate meters.

c. The failure condition is a dependent (secondary) failure as a result of an independent (primary) failure.

d. The failure is the result of damage caused by mishandling, abuse, or improper storage practices.

e. The failure condition is a direct result of improper test procedures or test equipment or improper maintenance (maintenance not in accord with applicable technical manuals or other maintenance documents).

f. Failure condition is the result of erroneous and/or ineffective rework of a previous failure condition.

g. Failure consists of physical discrepancy which does not affect the functional performance of the vehicle subsystem.

h. Failures detected during flight which are the result of a misalignment or maladjustment by ground maintenance personnel.

i. Failures which result from fluid, fuel, or lubrication contamination introduced to the vehicle from external sources and subsequent testing proves that contamination levels are outside the limits of the applicable vehicle specifications.

j. The failure condition occurred as a result of having been subjected to operational limits beyond applicable operation instructions.

7.4.4.5 Deduction of Failures - Failures which have been analyzed as to cause, with an effective fix developed for implementation to preclude recurrence, will be deducted from the total chargeable failures.

7.4.4.6 Data Acquisition and Evaluation Process - Two factors shall be utilized to measure achieved mission reliability; cumulative operating time, and net chargeable failures. Failure evaluation to determine net chargeable failures and cumulative time to be utilized in the measurement of mission reliability shall be performed, as required, by the Contractor.

7.4.5 System Reliability Measurement

7.4.5.1 System Reliability Measurement Test Schedule - Measurement of system reliability shall be accomplished utilizing data derived from Contractor and Government flight test programs. A measure of achieved reliability will be available with the status reports provided as specified in the contract. All component time and failure data will be utilized to provide the broadest possible statistical base for conclusions.

7.4.5.2 System Success and Failure Criteria - For the purpose of measuring AAFSS reliability, System Reliability is defined as the probability that the AAFSS will successfully complete a mission assignment of designated type and profile under specified flight conditions without incurring a fault in any of its subsystems which would require unscheduled maintenance given that the AAFSS has been maintained in accordance with applicable instructions and is operationally ready at the time of mission assignment.

7.4.5.3 Chargeable Failures - Failures will be included in the computation of system reliability when one or more of the following conditions exist:

a. Multiple independent (primary) failure conditions detected on the vehicle during measurement time will be individually chargeable.

b. Involuntary stoppage caused by an independent (primary) failure condition; or forced stoppage judged necessary by the pilot or crew to prevent or eliminate airframe or engine damage and/or personnel hazard.

c. Failure condition as a result of fluid, fuel, or lubrication contamination where subsequent testing proves that the contamination levels are within the limits specified for use in the vehicle.

d. Undiagnosed failure conditions where failure symptom was detected and verified in subsequent retesting at the bench test level but diagnosis and determination of the basic cause could not be established.

e. Failure is induced in GFM by installation characteristics. Failure induced by such characteristic shall be chargeable to CFM reliability.

7.4.5.4 Nonchargeable Failures - Failures will be excluded from the system reliability computation when one or more of the following conditions exist:

a. The failure symptom detected at the vehicle cannot be duplicated during subsequent retest.

b. The failure symptom is detected on the vehicle when time is not being recorded by the appropriate meters.

c. The failure condition is a dependent (secondary) failure as a result of an independent (primary) failure.

d. The failure is the result of damage caused by mishandling, abuse, or improper storage practices.

e. The failure condition is a direct result of improper test procedures, test equipment or improper maintenance (maintenance not in accord with applicable technical manuals or other maintenance documents).

f. Failure condition is the result of erroneous and/or ineffective rework of a previous failure condition.

g. Failure consists of physical discrepancy which does not affect the functional performance of the vehicle subsystem.

h. Failures detected during flight which are the result of a misalignment or maladjustment by ground maintenance personnel.

i. Failures which result from fluid, fuel, or lubrication contamination introduced to the vehicle from external sources and subsequent testing proves that contamination levels are not within the limits of the applicable vehicle specification.

j. The failure condition occurred as a result of having been subjected to operational limits beyond applicable operational instructions.

7.4.5.5 Deduction of Failures - Failures which have been analyzed as to cause, with an effective fix developed for implementation to preclude recurrence, will be deducted from the total chargeable failures.

7.4.5.6 Data Acquisition and Evaluation Process - Two factors shall be utilized to measure achieved system reliability: cumulative operating time, and net chargeable failures. Failure evaluation to determine net chargeable failures and cumulative time to be utilized in the measurement of system reliability shall be performed, as required, by the Contractor.

7.4.6 Weapon Subsystem Reliability Measurement

7.4.6.1 Weapon Subsystem Measurement Test Schedule - Measurement of Weapon Subsystem reliability shall be accomplished by live firing in the aircraft both air and ground. All firing conducted during the entire flight test program, both Contractor and Army, shall be used for this purpose to the extent possible.

7.4.6.2 Weapon Subsystem Success and Failure Criteria - Weapon Subsystems reliability shall be expressed in terms of Mean Rounds to Stoppage (MRTS). For the purpose of measuring Weapons Subsystems reliability to the objectives of 6.1.4.3, the criteria given in Paragraph 7.4.4.2 shall apply.

7.4.6.3 Chargeable Failure - Failures shall be included in the computation of weapon subsystem reliability when one or more of the following conditions exist:

a. Multiple independent (primary) failure conditions detected on the vehicle during measurement time will be individually chargeable.

b. Involuntary stoppage caused by an independent (primary) failure condition; or forced stoppage judged necessary by the pilot or crew to prevent or eliminate airframe or engine damage and/or personnel hazard.

c. Failure condition as a result of fluid, or lubrication contamination where subsequent testing proves that the contamination levels are within the limits specified for use in the vehicle.

d. Undiagnosed failure conditions where failure symptom was detected and verified in subsequent retesting but diagnosis and determination of the basic cause could not be established.

e. Failure is induced in GFM by installation characteristics. Failure induced by such characteristic shall be chargeable to CFM reliability.

7.4.6.4 Nonchargeable Failures - Failures will be excluded from the weapon subsystem reliability computation when one or more of the following conditions exist:

a. The failure symptom detected at the vehicle cannot be duplicated during subsequent retest.

7.4.6.4 (Continued)

b. The failure symptom is detected on the vehicle when time is not being recorded by the appropriate meters.

c. The failure condition is a dependent (secondary) failure as a result of an independent (primary) failure.

d. The failure is the result of damage caused by mishandling, abuse or improper storage practices.

e. The failure condition is a direct result of improper test procedures, test equipment or improper maintenance (maintenance not in accord with applicable technical manuals or other maintenance documents).

f. Failure condition is the result of erroneous and/or ineffective rework of a previous failure condition.

g. Failure consists of physical discrepancy which does not affect the functional performance of the weapon subsystem.

h. Failures detected during flight which are the result of a misalignment or maladjustment by ground maintenance personnel.

i. Failures which result from fluid, or lubrication contamination introduced to the vehicle from external sources where subsequent testing proves that contamination levels are outside the limits of the applicable vehicle specification.

j. The failure condition occurred as a result of having been subjected to operational limits beyond applicable operational instructions.

7.4.6.5 Deduction of Failures - Failures which have been analyzed as to cause, with an effective fix developed for implementation to preclude recurrence, will be deducted from the total chargeable failures.

7.4.6.6 Data Acquisition and Evaluation Process - Two factors shall be utilized to measure achieved mission reliability: cumulative operating time, cumulative rounds fired, and net chargeable failures. Failure evaluation to determine net chargeable failures and cumulative time and rounds fired to be utilized in the measurement of weapons subsystem reliability shall be performed, as required, by the Contractor.

APPENDIX B

CONTRACTUAL REQUIREMENTS FOR MEASURING RELIABILITY FOR THE T700 ENGINE

3.40 Reliability. The engine shall achieve the specified reliability value of 1200 hours Specified Mean Time Between Failure based upon decision risks of 10 percent and a discrimination ratio of two to one. This value is subject to the failure definitions and exclusions specified in 3.40.3 and 3.40.4.

3.40.1 Engine Design Life. The engine shall have a design life of 5,000 hours, with an initial target of 1,500 engine operating hours MTBFRO (Mean Time Between Failure Requiring Overhaul) at completion of the Post Qualification Reliability Demonstration Test Program. The 1,500 hour MTBFRO is based on the criteria of "on condition" maintenance and the load spectrum below.

(a)

% INTERMEDIATE ENGINE POWER	% ENGINE LIFE AT THIS POWER
100	15
75	45
55	25
35	10
IDLE	5

(b) Two start cycles per hour, with at least half of the starts made after the engine has cooled to ambient temperature.

The basic engine and all related components shall be designed for a minimum life of 5000 hours when operated at rated temperature levels according to the loading schedule of (a) above.

3.40.2 Engine Reliability Objectives. Reliability objectives to be reached at 17,000 engine operating hours of accumulated experience after qualification are shown below. These Mean Engine Operating Time Between Failure (MEOTBF) objectives shall not be degraded by more than 10 percent due to storage in approved storage container (without any maintenance or restoration) for a period not to exceed six calendar months.

Failure Classes	Engine MEOTBF (Hours)
I	1,250,000
I/II	303,000
I/II/III	6,300
I/II/III/IV	3,000
I/II/III/IV/V	1,800

3.40.3 Definitions.

(a) Mean Time Between Failure (MTBF). The total engine operating time of a population of engines divided by the total number of relevant events of engine failure experienced within the population during the measurement interval.

(b) Failure. Inability to perform required function within specified limits.

(c) Failure Requiring Overhaul (FRO). Failures in which corrective maintenance is sufficiently extensive to be beyond the capability of the organizational or direct support level; i.e., best performed at depot level (typically this will include major lube system contamination cases, main engine bearing failures, etc.).

(d) Failure Classes:

Class I - Failures that result in destruction of an engine or loss of aircraft control or fire external to the engine.

Class II - Failures which result in In-Flight shutdown (i.e., unrecoverable power loss).

Class III - Failures which result in potential power losses completely or partially rectified by automatic or manual corrective action.

Class IV - Failures which result in power loss or no start.

Class V - Failure which requires unscheduled maintenance action.

(e) Power Loss. Inability to obtain and/or sustain at least 90 percent of the desired power level.

(f) Primary Failure. An independent failure, not as a result of another failure.

(g) Secondary Failure. Any failure within the engine which was the result of some other failure.

3.40.4 Excluded Failures. The following exclusions apply in computation of the Reliability values stated in 3.40 and 3.40.2.

(a) Failures resulting from errors of maintenance personnel.

(b) Failures resulting from operating the engine beyond specification limits. Included failures are those operationally related failures for which engine provides integral protective devices (overspeed, overtemperature, hot starts).

(c) Failures resulting from airframe components.

(d) Failures to start if a successful start is accomplished without corrective maintenance action.

(e) Reported operating malfunctions which cannot be verified by subsequent investigation, flight or ground test.

(f) Multiple part removals and other maintenance actions performed upon the same engine following an initial failure requiring maintenance action will be counted as one failure against the engine.

(g) Failures of equipment not furnished by the engine contractor.

(h) Failures for which a corrective engine design change or an operational procedure change has been demonstrated, and approved by the Government, will be removed from the failure count, unless the events are identical to those for which corrective action was taken and it has been determined that the prescribed corrective action procedures have been utilized.